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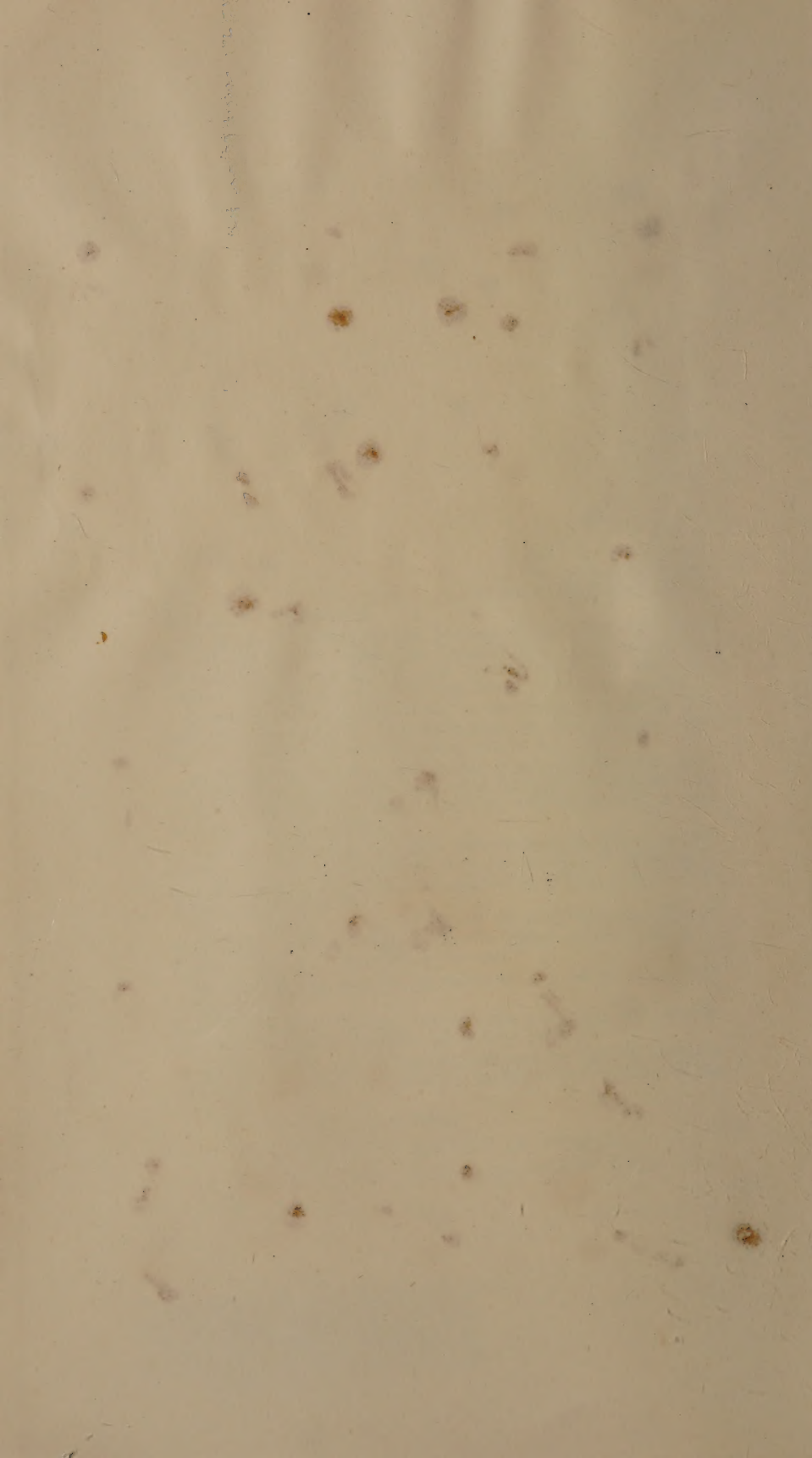
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and their efficient utilization for the use of students
and technical men in industry

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CORRIGENDA AND ADDENDA TO SECOND EDITION (1958)

Page

- 12 line 22: for "found" read "formed".
- 85 Table 3, 1st column: for "Scottish cashed peas" read "Scottish washed peas".
- 105 Fig. 1 } Equation $C + 2H_2 = CO_2 + 2H_2$
- 116 Fig. 1 } should read $C + 2H_2O = CO_2 + 2H_2$.
- 177 below Table 7: for "RADIATION OF" read "RADIATION FROM".
- 274 line 1: for "nearly of" read "nearly or".
- 333 line 1: amend to read "solution or suspension in the feed-water will be deposited at some point in the circuit".
- 369 line 4 from foot: for "date" read "data".
- 540 line 5 from foot: for "Chap. 9" read "Chap. 19".
- 834 line 1: delete "Low".

PREFACE TO THE FIRST EDITION, 1944

MANY and hard are the lessons taught by the stress and strain of war. Not the least amongst those that emerge from the present conflict has been the realisation by the British people of the value of their coal resources. There is a danger that the supply of fuel will be inadequate to maintain industrial activity to its fullest extent, and, as a consequence, the vital supply of munitions will be interrupted. To meet this situation the Fuel Efficiency Campaign has been organised by the Ministry of Fuel and Power; and amongst the instruments of that movement were the emergency training schemes undertaken jointly by the Board of Education and the Ministry to spread the knowledge of the efficient methods of using fuel.

It was soon realised that no single existing text-book covered both the fundamental principles and the essential operative features necessary to attain immediate results. The help of leading fuel technologists was therefore enlisted by the Education Sub-Committee of the Fuel Efficiency Committee, and a syllabus for the guidance of lecturers and a series of lecture notes that could be given to students were drawn up. In the course of preparing this material, however, it was soon realised that only the barest information could be given and the urgent need for a more comprehensive text-book on Fuel Efficiency was disclosed. Moreover, the favourable reception accorded to the Sub-Committee's earlier effort was a further incentive to the preparation of an extended and illustrated text-book, embracing the use of all fuels for industrial purposes.

The present work is the outcome of this effort. Its preparation has been entrusted by the Sub-Committee to the General Editorial supervision of Dr. G. E. Foxwell. Many leading authorities have generously assisted in its compilation and Dr. Foxwell has himself contributed substantially to the preparation of the subject matter. Each individual chapter has been submitted for approval to panels of experts on the particular subjects under review, and they have in many cases subjected them to certain criticism and revision. It is thus apparent that every means has been taken to ensure that the book is as authoritative as possible, free from personal bias and appreciative of the practical outlook.

It is not intended as a book of reference to be placed on the shelves of libraries and to which occasional reference is made. Each chapter is meant to be read by the student, and though it may be that one individual will not read them all, he will select those in which he is interested, and possibly become interested in some of the others.

The book was originally intended to emphasize the "application of knowledge," and arising out of this attempt to be practical, the preparation of certain chapters has indicated where information is lacking, and the Committee hopes to explore these untrodden paths in the near future.

In spite of the efforts made to present an effective work, the book has been prepared under emergency conditions and the need for haste has been uppermost. It has been done by busy men and many imperfections may accordingly be apparent. For these indulgence is asked, and it is requested that they may be pointed out so that they may be removed or corrected in future editions.

Further, it is hoped that this work may be regarded as part of a live and progressive movement, directed not only to the betterment of the present supply situation, but to an improvement in the efficient use of our greatest mineral asset. It may not be possible to say how long our coal resources will last, but it is possible to ensure that most may be made of their potential value.

The Education Sub-Committee cannot refer too highly to the skill and enthusiasm shown by Dr. Foxwell in the editing of this work. Their cordial thanks are offered to Mrs. Fuller for her share in piloting the work through its preliminary drafts, revision and proof reading.

Grateful acknowledgement is accorded to those mentioned below, for having taken part in the production of this work, and for their generous and able assistance, always given so freely and promptly. Thanks are extended, in no less a degree, to all those who have assisted but remain anonymous.

R. J. Sargent

E. Foxwell

PREFACE TO THE SECOND EDITION

THE First Edition of this book, issued in 1944, was prepared in an atmosphere of urgency, under war conditions. It was designed by the Education Sub-Committee of the Fuel Efficiency Committee of the Ministry of Fuel and Power to give the essential facts that should be known to engineers and chemists who, not being professional fuel technologists, had control of boilers, furnaces and other plant using fuel or applying heat as part of wider duties, administrative or technical.

During the fifteen years that have passed since the preparation of the previous volume was undertaken, the practice and science of fuel technology have advanced substantially. New ideas and processes, improved designs of fuel plant, better methods in utilization have been introduced. During this period the knowledge and practice of fuel technology have become more widespread. As a result some of the more elementary treatment adopted in parts of the First Edition has been modified appropriately.

The demand for fuel has outstripped home-produced supplies and, from being an exporter of fuel, this country has become, and for the foreseeable future will remain, a net importer. Every effort should, therefore, be made to use fuel as efficiently as possible in order to restrict to the bare minimum what the country imports. The answer lies in education, to which it is hoped this new edition will contribute.

The Education Committee of the then Ministry of Fuel and Power, believing that the time had come to review the original work, decided to seek the assistance of a large number of specialist authors to revise the work in order to bring the treatment into line with modern ideas, and to add new material. As a result of this review, although a few chapters have not been greatly changed, much had to be re-written. New material has been provided on water-tube boiler design, boiler auxiliary plant, furnaces, instrumentation and many other subjects and the chapters on Heat Transmission and The Flow

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of Fluids have been completely re-written. There are now included up-to-date (1957) accounts of the National Coal Board Code Number Classification of Coals, and of the International Classification drawn up under the *aegis* of the Coal Committee of Economic Commission for Europe. When the book went to press, the revision of the British Standard on sampling solid fuels had not been completed; it could not, therefore, be included. As much of the principles as are known to form the basis of the new Standard has been incorporated.

The Education Committee, and in particular the Chairman and Members of the Text-book Sub-Committee, take this opportunity of thanking all those who have so willingly and enthusiastically assisted in the work at a time when most of them were already fully engaged in the normal duties of their businesses or professions. Particular thanks are due to the Editor, Dr. C. Forrester, of the Ministry of Power, for his painstaking work not only in carrying out an onerous task, but also in contributing much of the new material and incorporating useful additional features.

R. J. Sargent

Chairman, Education Committee.

12th March, 1957.

J. E. Foxwell

Chairman, Editorial Panel.

It is with very great regret that we record the untimely death of Dr. Foxwell, which occurred on 26th April, 1957. On behalf of the Education Committee I take this opportunity of paying a tribute to his memory.

His contribution to the production of this work has been invaluable, both in the editing of the First Edition and as Chairman of the Editorial Panel producing this edition. A prolific worker devoting himself most effectively to many aspects of Fuel Technology, he never spared himself in taking the greatest practical interest in this Second Edition.

R. J. S.

NOTE

In preparing this revised edition the Concise Oxford Dictionary, and standards such as those issued by British Standards Institution, have in general been followed, though slavish adherence to these has not been meticulously adopted where common usage may have indicated to the contrary, nor has it proved practicable to achieve absolute uniformity where acceptable alternatives have appeared in text submitted by authors contributing to the work. The accepted abbreviation for the British Thermal Unit, now B.t.u., has been adopted, though in some cases the earlier abbreviation B.Th.U. may appear in illustrations owing to the necessity to use existing blocks. Temperatures in the Fahrenheit (or Centigrade) scale are not converted into the exact Centigrade (or Fahrenheit) equivalents in those cases where the temperatures are obviously approximate.

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CHAPTER 1

INTRODUCTORY

FUEL CONSERVATION

WHEN this book first appeared, in 1944, the need for conservation of the nation's (Britain's) national fuel resources was still vitally important. The war was not yet over and although the end was in sight it was clear that peace would not bring with it a solution for Britain's or other people's problems deriving from fuel shortage.

Although the stress of war-time conditions is not now with us, the need for using fuels efficiently so as to get the best out of them and, as a result, achieve economies, still remains as a duty. And it is a duty we owe not only to Britain but to all other countries making similar demands on the world's resources.

The world's resources in coal and petroleum are not inexhaustible. Expressed in terms of coal equivalent they have been estimated at something of the order of 5 million million tons. It is true that estimates made from time to time appear to prove the inaccuracies of earlier ones, but even though we do not know with certainty how much coal, petroleum and other "fossil" fuels remain in the earth, we do at least know with some certainty that as they are being used up they are not being replaced.

The seriousness of the problem increases year by year because the population of the world is increasing rapidly and because of the increasing industrialization of countries already well developed and the more recent industrialization of those not hitherto well developed.

WORLD POPULATION

Fifty years ago the population of the world was of the order of 1,600 million; by 1954 it had grown to about 2,600 million. If that rate of growth (50 per cent. every fifty years) were to continue, the population would be about 3,600 million by the year 2000 and it might by 2050 be over three times what it was in 1900. Not only so, but the most spectacular rates of growth have occurred in those countries in which industrial development will probably now increase most rapidly. The world's demand for fuel and power within the next hundred years may well rise to something of the order of four times the present demand, i.e. from about 3,650 million tons of coal (or its equivalent) to about 15,000 million tons.

Much higher and more alarming estimates have been made, and will no doubt be made in the future. All may be considered to be, at the best, intelligent guesses based on data of varying degrees of reliability and validity. But the broad picture remains the same; the world's stores of fossil fuels should be used most carefully and the fullest possible use should be made of all the resources of human ingenuity in the joint fields of fuel technology, combustion engineering, power production and manufacturing processes.

The state of industrial development of a country and its standard of living may be measured in terms of the annual fuel consumption per person. The amount of coal consumed for all purposes, in 1954, in the U.S.A. was 8.0 tons, the figures for Britain and India being 4.8 and 0.3 respectively. The figure for India is practically the same as it was 50 years ago, whereas that for the U.S.A. has risen from 5.2 tons. It may be assumed that if accurate figures could be obtained the picture in respect of such countries as China and Indonesia would present even greater contrasts. When such countries develop

so as to place in the hands of the working population a greater amount of power, whether as fuel or as electrical energy, the effect on the overall figure for world demand will be enormous.

Judged by the criterion of increasing demands for fuels, purely on a tonnage basis the outlook can indeed be gloomy. On the other hand, rapid improvements in technique and the steady increase in efficiency of fuel utilization and power production offer a glimpse of the silver lining behind the cloud.

SPECIAL FUELS

Whatever overall shortages may occur in fuels, particularly in coals, they will almost certainly occur more in respect of some requirements than for others. Metallurgical operations, for example, at present demand adequate supplies of high quality hard coke, for the making of which only certain types of coals are at present suitable. There is good reason to fear that a shortage of coking coals may be experienced long before a more general shortage of fuels occurs. The development of new techniques in hard coke making and in metallurgy will, on the other hand, relieve the situation.

PETROLEUM RESOURCES

The general position can to some extent be relieved by the world's resources in petroleum, but the most generous present estimates suggest that the total of these resources can represent little more than about 3 per cent. of the thermal value of the resources in solid fuels. Even including the natural gas generally associated with petroleum and the methane associated with coal, the total would probably not be more than 6 per cent.

OTHER SOLID FUELS. OIL SHALE, PEAT

Available information suggests that the oil from shale deposits can be considered to amount to about one per cent. of coal equivalent, and reserves of peat probably represent about $1\frac{1}{2}$ per cent. Ignoring for the present the bituminous tar sands of Alberta, it is clear from these estimates that in all probability coals and lignites represent well over 90 per cent. of the world's resources of fossil fuels.

The Alberta deposits above referred to are still the object of much speculation. Technical details of production have not yet been worked out and estimates vary widely, even wildly, from as little as 100 million tons of oil to 40,000 million tons. This latter figure is still small compared with the reserves of accessible solid and liquid fuels which the more conservative estimates place at 4-5 million million tons as quoted above.

OTHER SOURCES OF ENERGY

There are, of course, other fuels and sources of energy. Wood and other cellulosic materials are valuable fuels where they grow or accumulate, and substances such as bagasse (the refuse from sugar cane extraction) and even foodstuffs (e.g. surplus coffee beans and grain stuffs) come to mind. The droppings of animals (especially, in eastern countries, cow dung) are a valuable domestic fuel whose use, of course, deprives the soil of more urgently needed fertilisers. These sources probably account for about one-twelfth of the total annual consumption of fuels throughout the world, but equally probably at the cost of more valuable alternative potential uses. The world's forests might provide the equivalent of about a quarter of present requirements, but it is perhaps doubtful whether a universal practicable scheme could be worked out for their use.

Water power is an important alternative to coal and other fuels. The world's resources have been estimated to give the equivalent of power that could be obtained from 3,500 million tons of coal a year. This is almost equal to the world's total consumption of fuel and energy in 1954. Only about one-fifteenth is actually in use at present. It is early yet to speculate on the extent to which nearly full use can ultimately be made of water power.

The possibilities of tidal power being harnessed are still in the realm of theory and small-scale experiment, and estimates must, by the very nature of the problem, be of an extremely speculative nature. One estimate suggests that if all the tidal power possibilities that had been discussed were practicable the electrical energy obtained would be equivalent to an annual consumption of more than 2,000 million tons of coal. The prohibitive costs of putting any of the proposed schemes into practice has hitherto ruled them out though it has recently been decided in France to harness tidal power near St. Malo. The capital cost of this scheme has been estimated at £35 million.

Wind power also offers possibilities and several schemes have reached the stage of large-scale pilot plants. Many thousands of small windmills are, of course, operating throughout the world, mainly for pumping water, some for small-scale electricity generation. The possibilities in this field are probably more attractive than are those for developing tidal power. Even so, world estimates of the equivalent of about 7,000 million tons of coal a year from wind power must still be considered as highly speculative.

It has been estimated that the net amount of heat reaching the earth's surface from the sun is about 5,000 times the amount of heat we get from burning solid, liquid and gaseous fuels. Only a microscopic amount of this could be used in a practical form for raising power; nevertheless, sun power has been used and experiments in this field are continuing. The outcome of these experiments is not likely materially to affect the world position in respect of the use of and need for more tangible forms of fuel resources.

NUCLEAR ENERGY. "ATOMIC POWER"

There remains the possibility of using nuclear energy, and here we enter a new field of human endeavour that had barely been considered as practicable when this book first appeared. The immense, indeed incalculable, possibilities of the utilization of nuclear energy inevitably raise the question: what effect will these new developments have on the world position in respect of shortage of fossil fuel.

There is as yet no simple answer to that question. No one can at this date say how accurate are the forecasts relating to the setting up of large power stations to be "fuelled" by fissile elements. It looks at present as if ten or twenty years must pass before the contribution from this new source of energy will have a substantial effect on the world position, and that coal will continue to be an indispensable industrial fuel. Not only so, but many hundreds of thousands of small factories throughout the world will still find fossil fuels more suited than electrical energy to their special requirements. Complete replacement of conventional steam boilers, if it ever does take place, will require several decades and implies another kind of industrial revolution. In the meantime, coal will still be required for a thousand and one purposes, and most present-day estimates of future requirements suggest that the present shortage will continue. It must be remembered that it is in any case as much a shortage due to limitation of the rate at which we can get the solid fuels out of the earth as a shortage of resources, an income shortage rather than a capital shortage.

Coal and other solid fuels must, therefore, still be used efficiently and

economically. This aspect is referred to again below in considering the position in Britain.

THE POSITION IN BRITAIN

This book is addressed primarily to fuel and power users in Britain; inevitably, therefore, its approach is that of catering for Britain's present and future need. Considering all the available facts, there can be little doubt that for several decades coal will continue to be the nation's most important source of heat and power.

COAL RESOURCES

Britain's reserves of useful and accessible coal are of the order of 170,000 million tons, of which she uses about 225 million tons a year, just over 10 million of which is being exported or used in ships' bunkers. The internal consumption of 215 million tons a year compares with 180 million tons used in 1910 when 50 million tons a year were exported. Substantial quantities are now being imported.

At the rate at which the reserves are being used up it might be suggested that they will last for several hundred years. The real difficulty facing the country is that of raising what is needed to the surface and that at an economic cost. All the industrial needs are not at present being supplied from indigenous sources: furthermore the increasing need to use coal as a raw material for the chemical and associated industries complicates the position, as indeed it does in other countries.

Even with the additional support to be expected from nuclear power all fuel resources, whether solid fuels or indigenous and imported liquid fuels, will be required; any margin of coal, therefore, released from the present or future requirements of power stations, will still be welcome, both for its direct intrinsic value as a fuel (solid or converted into oil) and for the sake of helping to meet the steeply rising demand for oil fuels. As far as can be judged from available information, and on the basis of present requirements and anticipated trends, for the next decade at least as much as 75 per cent. of Britain's power will be derived, of necessity, from home-produced coal. Only about 3 per cent. will be available from hydro-electric power and nuclear energy. What the succeeding decade will bring forth must, for the present, remain in the realms of speculation.

The lesson is, therefore, coal must still be used sensibly, efficiently and economically.

Tables giving statistical information and conversion factors that may be of interest to the enquiring student are given in Appendices at the end of this book. Some of the information is, necessarily, repeated at the appropriate pages throughout the book along with the more detailed information appropriate to the subject of each chapter.

For statistics relating to fuel and power resources and requirement trends see Appendix B.

CHAPTER 2

COAL AND THE OTHER FOSSIL FUELS

THE ORIGIN AND NATURE OF COAL

THE term *coal* is applied to those rocks in the earth's crust that have resulted from the accumulation millions of years ago of decayed plant remains and from their subsequent consolidation under the superimposed strata by a complex series of chemical and physical changes. Shales impregnated with carbonaceous matter (oil shales) are excluded from the definition. Scientists have found in coal traces of the structures of plant and portions of trees that have suffered only slight changes in form.

Two theories have been put forward as to the modes of origin of coal seams. The first—the growth-in-place or *in situ* theory—says that the coal seam occupies more or less the site on which the original plants grew and where their remains accumulated. According to the second—the “drift” theory—material composing the coal seams drifted there from the areas in which it grew, the site of a seam commonly representing a lake or estuary in which it was deposited.

The Great Dismal Swamp of Virginia in North Carolina illustrates present-day conditions similar to those in which some of the world's coal seams were undoubtedly deposited. The water is shallow and the bed below consists of ten to fifteen feet of partly decayed roots (*in situ*), the trunks, branches, leaves, and seeds of the continually falling trees, producing a mass relatively free from soil and other earthy materials. An example of the drift method of deposit is seen in the large quantities of material—vegetable matter, trunks, branches, etc.—deposited along with fine silt by the Mississippi River at its estuary, where the waterlogged vegetable matter sinks and is deposited on the muddy floor of the estuary.

DECOMPOSITION OF VEGETABLE MATTER

On dry ground, fallen trees and other plant remains are attacked by oxygen of the air, the cellulose (their chief constituent) being converted into water and various gases so that it soon rots away, leaving practically no trace. Under water, however, when air is excluded (and, therefore, oxygen is not available) the plant remains are decomposed by the action of bacteria. The decomposition products accumulate until the bacteria can no longer live.

Certain parts of plants are more resistant to attack than others; the result is that some fragments of plants, particularly spore exines (the tough outer jackets of spores), bark, or its cuticle (outer skin) can be clearly identified.

As a result of geological influences causing the surface of the land relative to the sea to fall and rise alternately, the accumulations of decayed plant material became covered by layers of sediment and rocks, in between which more layers of plant remains became deposited. In this way a sequence of coal seams has been built up.

The changes that followed the end of bacterial decay may have been even more profound, under the influences of heat and pressure. In some cases the heat has been due to intrusions of molten igneous rocks from below; but much of it, perhaps most, has resulted from the pressure. Pressure resulted not only from the weight of overlying strata, but also from powerful lateral earth movements causing folding and compression of the seams. Chemical action resulted from all this, and included the elimination of water and of oxides of carbon. As all these agencies have varied in their intensities, the amount of material

remaining in the ultimate coal substance and that can be expelled from it by the action of heat in the form of volatile vapours and gases (the *volatile matter*) also varies considerably. The result is to produce a large variety of coals of different characteristics.

VARIATIONS IN COAL

The variations in the properties and characteristics of coal produced by these agencies may be considered under the following heads:

1. nature of the original vegetation and its separation by grading action of water;
2. extent of bacterial decay;
3. extent of removal of volatile matter by heat and pressure.

1. Continuous seams of coal are known, for example in South Wales, in which the character of the coal changes steadily as one proceeds across the coalfield. The result is a range of coals, *even within one seam*, from bituminous to anthracitic. Microscopical examination has shown that some types of plants are present over the whole area; the differences cannot, therefore, be accounted for by mere differences in vegetation. Segregation of different parts of similar vegetation can, however, produce marked differences in composition. For example, the dull bands (durain) that occur in many coal seams contain more plant remains than do the bright bands adjacent to them. Other plant fragments bear evidence of having been water-borne. This suggests some segregation of the parts of the plant by the action of water, producing a difference in the final coal.

2. The extent to which bacterial action proceeded was probably influenced by drainage, since bacterial decomposition normally continues until the products accumulate to such an extent as to arrest decay. It will be clear that coals resulting from geological action on vegetable material of different degrees of bacterial decomposition may have widely differing properties and characteristics.

3. The heat and pressure to which deposits have been subjected so as to produce coal depend upon the depth of the overlying strata and on the degree of earth movement. In areas where there has been relatively little earth movement and, in consequence, the seams have remained more or less undisturbed, the oldest seams (i.e. the lowest) contain less volatile matter than do those above, regular progression being the general rule. Although this rule, enunciated by Hilt¹ as a natural law, is of fairly general application, important exceptions occur.

Anthracite is the coal characterized by the smallest percentage of volatile matter. **Anthracitization* occurs in the north west of the South Wales coalfield, where there has been most geological disturbance. It is, therefore, likely that pressure and heat have been responsible for this lateral difference in properties. In Scotland, parts of certain seams have been changed into a pseudo-anthracite, locally called anthracite, simply by the heat of intruding molten magma.

SOME CONSTITUENTS AND CHARACTERISTICS OF COAL

In order to understand and appreciate the differences between types of coal it is necessary to understand the meanings of certain terms used. Most of these are defined and explained in British Standard 1016 "Methods for the Analysis and Testing of Coal and Coke"². The analytical determination of the amounts of these constituents is dealt with in Chapter 30.

* *Anthracitization*, a geological term indicating the progressive conversion, into anthracite, of vegetable remains, that might under less severe geological influences have produced bituminous coal.

CALORIFIC VALUE (C.V.)

For many purposes the most important property of a coal—or for that matter of any fuel—is its calorific value. The C.V. of coal is a measure of its heating power and is (a) the number of British thermal units (B.t.u.) liberated when *one pound* of the coal is completely burned in oxygen or (b) the number of calories (cal.) liberated when *one gramme* of the coal is completely burned in oxygen. The determination is carried out under standard conditions as prescribed in B.S.1016, Part 5.

MOISTURE

All coals contain free or surface moisture, i.e. water, that has percolated through the strata and workings of the mine. Surface moisture of a coal as delivered to the consumer may also be derived from the operation of wet cleaning processes or from exposure to rain (e.g. in transit from the colliery). This loosely adhering and frequently visible surface moisture can be dried off on exposure to the air, the coal thereupon being known as *air-dried*. The conditions necessary for measuring the amount of this “free” or surface moisture are as important as are the laboratory conditions for the other analytical tests. The coal dries, on exposure in a well-ventilated place protected from the weather, until its moisture content is more or less in equilibrium with the moisture in the surrounding air.

When the air-dried coal is heated under standard conditions (see Chapter 30) an additional amount of water is evolved. This amount is characteristic of the type of coal, as characteristic as are other of its measurable constituents, and is called *inherent moisture*. The amount, from well below 1 per cent. to more than 15 per cent. in the case of British coals, may in the case of some other coals and of geologically immature fuels such as lignite, be much higher.

ASH

The ash of coal is the incombustible matter of mineral origin left behind when the coal is burned. Its amount is determined in the laboratory by the complete combustion of a weighed sample, under carefully controlled conditions. It is made up of several different components, the material derived from shale, clay, pyrites, ankerites (white partings within the seam) and dirt from earthy or stony bands in the coal seam, and fragments of stone from the roof or floor of the seam. The ash derived from this material is termed *adventitious ash*. In addition to this material, the coal substance derived from the vegetable matter also contains incombustible mineral matter. This mineral matter is for all practical purposes inseparable from the coal substance; the ash derived from it is generally described as *inherent ash*.

In the course of the mechanical cleaning of coals much, but not all, of the adventitious ash-forming material can be removed; none of the inherent ash-forming material can in practice be removed.

The specific gravity of shale ranges from about 1.6 upwards. On immersing crushed coal in a liquid of sp. gr. about 1.6, material of high ash content sinks, the coal substance floats. Considered to be clean coal, this has an ash content generally below 4.5 per cent. By floating off fractions of coal on a selection of liquids of different specific gravities varying from 1.35 (or less) upwards a range of products can be obtained, the lightest having perhaps as little as 1 per cent. of ash.

MINERAL MATTER AND ASH

The ash that accumulates in the ash-pit of a furnace, or in the crucible in the laboratory, differs substantially from the mineral matter that was present

in the coal and from which it was formed. It is less than the original mineral matter by the amount of combined moisture and carbon dioxide expelled from clays and other minerals by the action of heat during the burning of the coal matter, and also by the difference in weight between any mineral matter originally present (e.g. iron pyrites) and the substance produced from it during combustion (e.g. in the case of pyrites, ferric oxide). As a matter of convenience, and for rough calculations, it may be said that in general the weight of ash obtained from a coal is about nine-tenths of the weight of the mineral matter originally present. That means that if a coal is described as having, say, 9 per cent. or 10 per cent. of ash the coal really contained 10 per cent. or 11 per cent. of incombustible ash-forming matter. There are wide departures from this somewhat rough-and-ready rule.

Owing to the wide variation in composition of the mineral matter that makes up the incombustible part of coal, this arbitrary 10 per cent. adjustment is not sufficiently accurate for scientific work. Correction formulae have been devised, based on a more accurate knowledge of the mineral matter present in coal. The formula recommended in B.S. 1016 is that of King, Maries and Crossley—the "K.M.C. formula"³.

This formula was recently (1956) revised by the National Coal Board and in its revised form states that the mineral matter, M.M., in coal equals:

$$1.13A + 0.5 S_{\text{pyr}} + 0.8 \text{CO}_2 - 2.8 S_{\text{ash}} + 2.8 S_{\text{sulph}} + 0.5 \text{Cl}$$

where, as percentages of the air-dried coal,

- A = ash obtained on incineration,
- S_{pyr} = pyritic sulphur in the coal,
- CO_2 = carbonate CO_2 in the coal,
- S_{ash} = total sulphur in the ash,
- S_{sulph} = sulphur present as sulphates in the coal,
- Cl = total chlorine in the coal.

Recently, by statistical examination of data collected for the purpose of applying the K.M.C. formula to large numbers of British coals, the staff of the British Coal Utilisation Research Association (B.C.U.R.A.) have established that certain correlations exist between constituents, and hence have derived a simplified formula which, while enabling the mineral matter to be calculated with reasonable accuracy, does not call for the special, time-consuming determinations required by the original formula. The simplified formula¹⁰, which requires only a knowledge of ash, total sulphur and total carbon dioxide, is as follows:

$$\text{M.M.} = 1.10A + 0.53 S + 0.74 \text{CO}_2 - 0.32$$

where M.M.=mineral matter,

A=ash,

S=total sulphur,

CO_2 =total carbon dioxide.

The Parr formula (U.S.A.) states that the mineral matter equals

$$1.08 A + 0.55 S,$$

where A = ash actually found and S = total sulphur.

It is based on the (incorrect) assumption that all the sulphur is present in the coal as pyrites and also takes no account of the carbon dioxide content, which is a significant factor in British coals. For these reasons the formula is not recommended for universal adoption.

VOLATILE MATTER

Volatile matter is defined as the percentage loss in weight resulting from the heating of one gramme of coal under standard conditions in a crucible

from which air is excluded (see Chapter 30). Although moisture also is volatile and is expelled at the same time, the percentage of moisture is always recorded separately; *volatile matter* does not, therefore, include moisture. The volatile matter expelled consists of:

- (a) water not originally present as either free or inherent moisture, but derived from the chemical decomposition of the coal and the shaly matter.
- (b) a complex mixture of combustible gases including hydrogen, methane, ethane, benzene, etc.;
- (c) tar, a complex mixture of hydrocarbons and other organic compounds, some of the latter, especially phenols, containing oxygen in their chemical composition.

Practically none of the volatile matter expelled from coal when heated existed as such in the original coal; the substances composing it are chemically formed as a result of disruption of the coal substance.

The percentage of volatile matter expressed as a fraction of the dry, ash-free coal, or preferably expressed as a fraction of the dry, mineral-matter-free coal, is a valuable guide to the character of the coal and its probable suitability for use in industry.

Calculation of Volatile Matter to dry mineral-matter-free basis

Owing to the evolution, during the volatile matter test, of volatile constituents of some of the inorganic mineral matter in coal, the amount of volatile matter actually expelled during the test is usually greater than the amount of (organic) volatile matter derived from the coal substance. Accordingly the following corrections are applicable as deductions from the volatile matter figure of the proximate analysis, all constituents being expressed as percentages of the air-dried coal:

- (a) in cases where both pyritic sulphur and chlorine have been determined,

$$0.13 A + 0.2 S_{\text{pyr}} + 0.7 \text{CO}_2 + 0.6 \text{Cl} - 0.20;$$
- (b) in cases where chlorine but not pyritic sulphur has been determined:

$$0.13 A + 0.2 S_{\text{total}} + 0.7 \text{CO}_2 + 0.6 \text{Cl} - 0.32;$$
- (c) in cases where neither pyritic sulphur nor chlorine has been determined,

$$0.13 A + 0.2 S_{\text{total}} + 0.7 \text{CO}_2 - 0.13.$$

The net amount of volatile matter, recalculated to the dry, mineral-matter-free basis is, of course, calculated by first applying the appropriate correction to the figure for V.M. on the air-dried basis and then multiplying the corrected value thus obtained by $100/(100 - \text{moisture} - \text{M.M.})$, i.e.

$$\text{V.M.}_{\text{d.m.m.f}} = \frac{(\text{V.M.} - \text{correction}) \times 100}{100 - \text{moisture} - \text{M.M.}}$$

PROXIMATE ANALYSIS

Three 'constituents' of coal, namely moisture, volatile matter and ash, have been discussed. There remains for consideration a fourth term used in coal technology, *fixed carbon*. The procedure of determining the percentages of moisture in the coal sample, volatile matter, fixed carbon and ash is termed "*proximate analysis*". The percentage of fixed carbon is not a figure determined by analysis in the laboratory; it is obtained by deducting from 100 the percentages of moisture, volatile matter and ash obtained by analysis. The term fixed carbon is, therefore, virtually a hypothetical concept, derived purely arithmetically. Its use does not imply the existence of uncombined carbon in coal, nor does it bear any direct relationship to the *total carbon* in coal as determined by an Ultimate Analysis (the procedure for which is discussed below). There is probably, in fact, no free carbon in coal. In this context, therefore, fixed carbon cannot be considered as a precise *constituent* of coal.

Full details of the methods used in proximate analysis are given in B.S.1016, Part 3. It should be stressed that the term 'proximate analysis' does not imply that only *approximately* accurate results are obtained or that the procedures are rough-and-ready ones needing little care. In fact, proximate analysis is an analytical procedure requiring the exercise of great care in the laboratory and strictest attention to conforming with the requirements of the British Standard (B.S.1016, Part 3) already referred to. The term is used only in contra-distinction to the term Ultimate Analysis, now discussed.

ULTIMATE ANALYSIS

The proximate analysis of a coal differs from a complete chemical analysis in that exact percentages of *elements* or of *chemical radicals* are not determined by the former procedure. Accurate chemical determination of the important chemical elements present in a coal constitutes what is known as *ultimate analysis*. The elements generally determined are: carbon, hydrogen, nitrogen and sulphur. For some purposes phosphorus, chlorine and arsenic are also determined.

The difference between 100 and the sum of the determined percentages of the above elements *plus* the percentages of ash and moisture of the air-dried coal is termed 'oxygen plus errors'. This is because there is, at present, no method that can be recommended for the analytical determination of oxygen in coal; its value can be obtained only as a 'difference figure'. The figure so obtained will be inaccurate since it will include the cumulative errors of the determination of the other elements. A more accurate value for oxygen may be obtained by conversion of the results to the dry, mineral-matter-free basis.

The details of the procedure in ultimate analysis of coal and coke are given in B.S.1016, Part 6.

The ultimate analysis of a coal is of very great practical, as well as scientific, value and the results of such an analysis are of particular interest to the research chemist and the fuel technologist. The percentages of carbon, hydrogen and oxygen are of special significance in connection with classification of coals and other fossil fuels. The sulphur and phosphorus contents of coal and coke are of importance to the metallurgist, especially in the metallurgy of iron and steel. Arsenic content is of importance in the brewing industry. The chlorine content of coals has attracted particular attention in recent years because of the light it throws on corrosion and its action, in the form of alkali salts, on the formation of bonded deposits in boiler systems.

SULPHUR AND PHOSPHORUS IN COAL

Sulphur

Sulphur is present in coals generally to the extent of 0.5–3.5 per cent. The average in British coal is at present about 1.5 per cent. Occasionally coals are met with containing much larger amounts—even (and particularly in some foreign coals) 10 to 20 per cent. It is present in the coal in three forms; about half the sulphur in British coals is usually present as pyrites (FeS_2), the remainder as "organic" sulphur compounds, with a much smaller amount as sulphates.

The amount of pyritic sulphur may vary considerably from one part of a seam to another, but that of organic sulphur is generally fairly constant throughout. This is illustrated by the following figures showing percentage occurrences at different positions from roof to floor in one seam:

Portion of seam:						Total	Sulphur—per cent.:	
Roof							Pyritic	Organic
E	..	..	..	..	..	5.26	3.60	1.66
D	..	..	..	..	..	1.86	0.60	1.26
C	..	..	..	..	..	1.79	0.35	1.44
B	..	..	..	..	..	3.27	1.68	1.59
A	..	..	..	..	..	2.44	0.99	1.45
Floor								
Whole seam						2.62	1.25	1.37
Thin unworked coal below seam. . .						12.61	11.14	1.47

Under the action of heat, pyritic sulphur in a coal is partly evolved in the form of free sulphur according to the reaction $\text{FeS}_2 = \text{FeS} + \text{S}$; this reaction occurs at about 500°C . (930°F .) and much of this sulphur combines with hydrogen of the coal during carbonization or burns to SO_2 during combustion. A proportion of the sulphur first liberated may form so-called organic sulphur compounds, particularly during carbonization. The remaining sulphur left in the form of FeS may behave in two ways, according to the conditions. In the presence of ample supplies of oxygen it may be oxidized according to such reactions as $4\text{FeS} + 7\text{O}_2 = 2\text{Fe}_2\text{O}_3 + 4\text{SO}_2$; or the ferrous sulphide may form ferrous silicate with other constituents of the ash, with the liberation of sulphur; this reaction assists the formation of clinker, as ferrous silicates are very fusible.

Iron pyrites is one contributory cause of clinker formation owing partly to the relative fusibility of iron sulphide (1193°C .) and partly to the subsequent formation of ferrous oxide or silicate.

Some of the sulphur present as pyrites in coal can be removed by appropriate cleaning methods, but much remains in the cleaned product, especially if the pyrites occurs in a finely disseminated form. Ordinary cleaning processes have practically no effect on sulphur present in an organic form.

All volatile sulphur is burned mainly to SO_2 in the course of combustion. At high temperatures sulphur present as sulphate is partly expelled as sulphur trioxide, SO_3 . Sulphur is thus objectionable for the following reasons:

- (1) Oxides of sulphur contaminate the atmosphere, forming sulphurous and sulphuric acids, which may cause serious damage to property and impair health.
- (2) When a fuel containing hydrogen is burned, the hydrogen forms water vapour. If the temperature of the gases falls too low, for example on the surface of an economiser, some of the water is condensed, and the oxides of sulphur are absorbed by this water, forming a solution of sulphurous and sulphuric acids. This may be the cause of severe corrosion of the metal. The presence of SO_3 in flue gases has been shown to raise the dew-point of the gases materially and thus to increase the danger of deposition of acids on the metal.
- (3) Part of the sulphur may be absorbed by inter-action with the grate bars, forming sulphide of iron; since sulphide of iron is readily fusible, it may cause serious trouble.
- (4) When the coal, or coke made from it, is used for metallurgical purposes the sulphur may pass into the metal under treatment.

Phosphorus

The amount of phosphorus in coal rarely exceeds 0.1 per cent. and is usually much less. This constituent is of importance in metallurgical coke; the phosphorus content of blast furnace coke should not exceed 0.01 per cent.

when the pig iron is to be made into steel by the acid process, i.e. in the open-hearth furnace with silica lining. When steel is made by the basic Bessemer process the phosphorus in the pig iron is removed by combining with the furnace lining and in this case high-phosphorus cokes can be used. Phosphorus is a constituent of the inorganic mineral matter in the coal and all the phosphorus originally present in the coal is retained in the coke on carbonization.

CAKING AND SWELLING PROPERTIES

The caking or agglutinating properties of a coal are of particular importance to the coking and gas industries. Serious damage can result to the coke ovens if an undue swelling pressure occurs. Caking is highly important during combustion on a firegrate. (See Chap. 8.). Methods of measuring these properties, therefore, occupy an important place among the many standard tests to which solid fuels are customarily submitted.

Cause of Caking

The cause of the property of "caking" or "caking" has been the subject of research for more than fifty years. A simple explanation in line with modern thought is that from a caking coal there are liberated under the action of heat at temperatures of the order of 340° to 450° C. substances which cause the main mass of the coal to become more or less fluid, a condition described as "pasty" or "plastic". Coals from which very little such material is formed are either non-caking or weakly caking. Whether such compounds are found or not depends on the composition of the coal. The more plastic a coal becomes on heating the stronger is its caking power. Plastic softening is now believed to be due to three causes:

- (a) Production from the coal, by decomposition through heat, of a fluid that plasticises the remainder of the coal.
- (b) Fusion of low-molecular-weight organic constituents of the coal;
- and (c) Lubrication of the structural, non-fusible units by mobile surface films formed by either of the foregoing reactions.

Coal is charged into the coke oven or gas retort in the form of small pieces or fines mostly below $\frac{1}{8}$ in. in size. As the coal becomes plastic under heat, gases are evolved within the plastic material which set up pressure, often considerable, that assists in binding the now partially fluid grains together. The grains or pieces lose their identity in a plastic mess which, as the gas escapes, forms the cellular material, coke.

At lower temperatures, 300 – 450° C., coals decompose slowly, but a temperature is reached, usually after the coal has become plastic, say 450 – 500° C., at which decomposition is rapid and the coal hardens into coke. It is a further condition to be fulfilled before a coal will coke in practice that the plastic stage must precede the stage of rapid decomposition.

Assessment of caking power

The nature of the solid residue from the volatile matter test is a guide to the ability of a coal to form a good coke. As conducted in the laboratory using the standard crucible prescribed, the test does not give a sufficiently accurate measure of caking properties. Several other tests have been developed either for indicating caking and swelling properties, e.g. the Swelling Index, the Roga Index, the dilatometer test and the Gray-King assay. Among the earlier tests devised for throwing light on these properties was that developed by Lessing which, using compact and easily operated equipment, gave useful information regarding the swelling and caking properties of a coal and the amounts of gas and tar produced during carbonization.

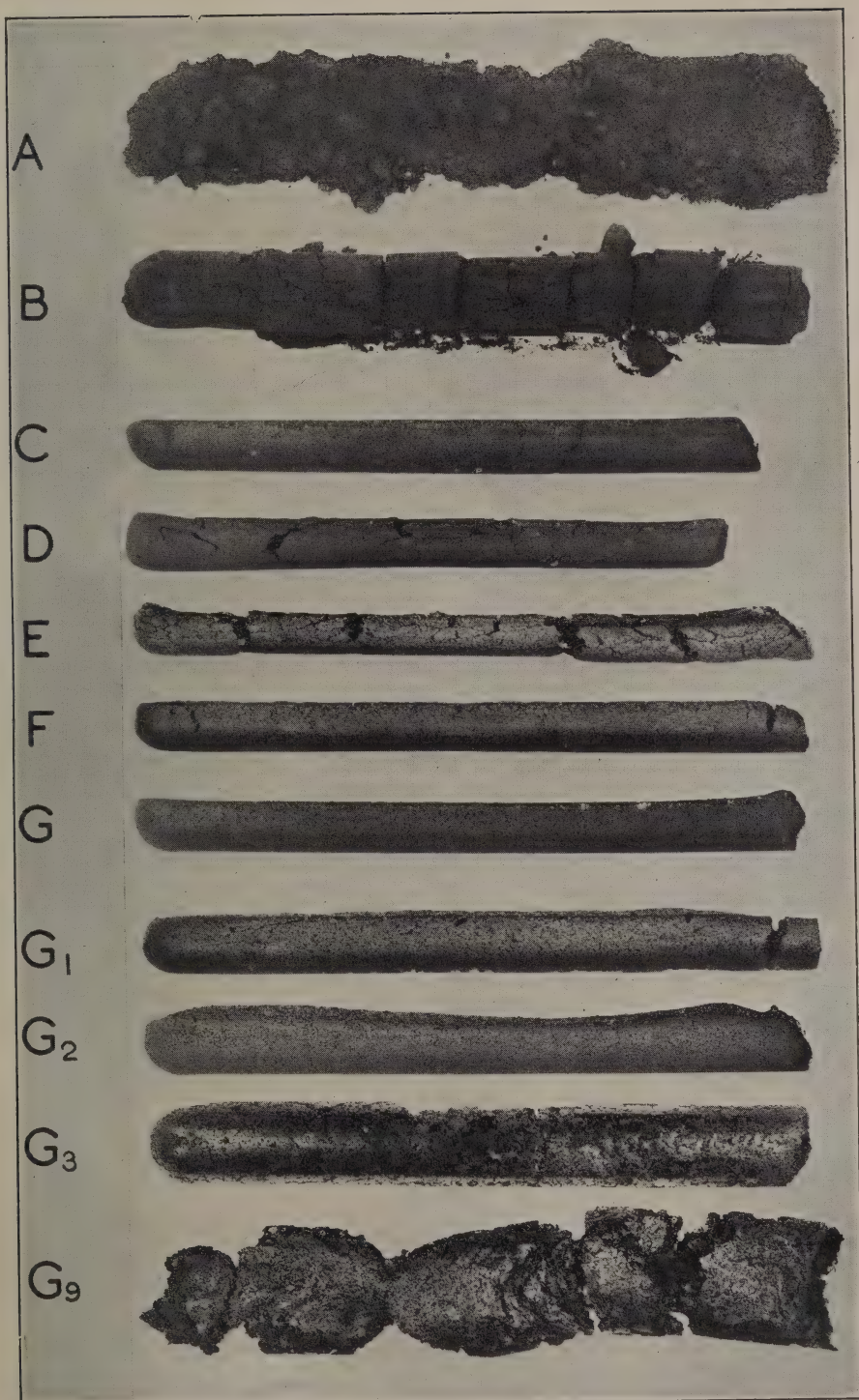


FIG. 1. Cokes from the Gray-King Assay.

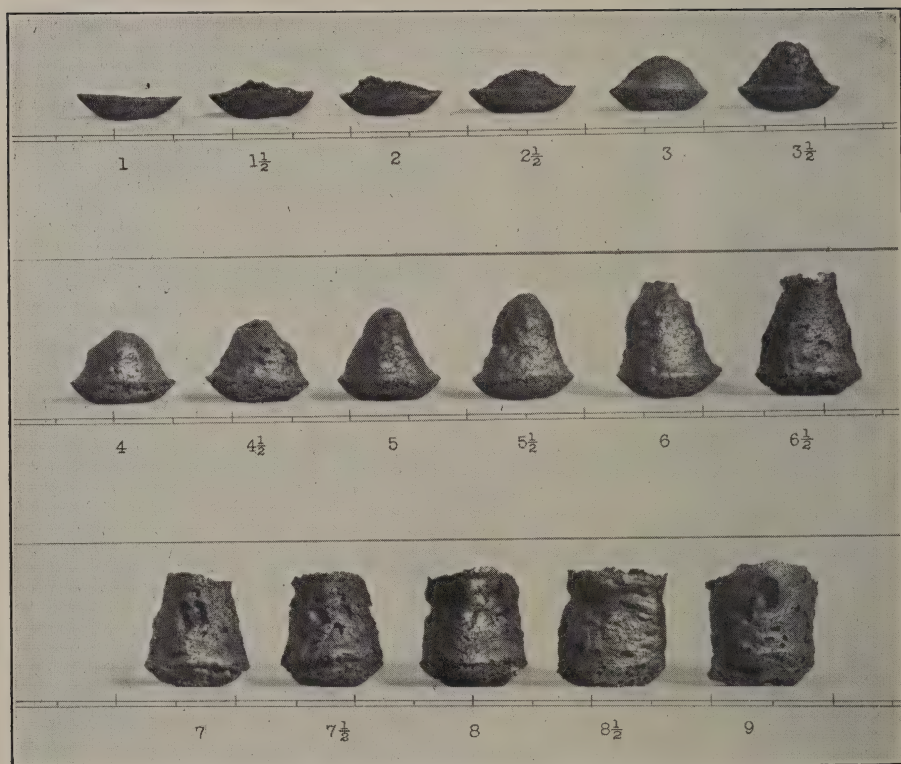


FIG. 2. Coke Profiles from the B.S. Swelling Test.

The test in B.S.1016 has been developed from the Gray-King assay ^{4,5}. In this test 20 g. of the coal are heated in a silica tube in a standard furnace at a defined rate of rise of temperature to 600° C. (1,110° F.). The appearance of the resulting residue is then compared with a series of standard cokes, to which the letters A to G are allocated, and its position in the series is determined. The series ranges from *non-caking* up to a *highly caking* coal. Coals of type A are non-caking and those which give a hard strong coke, but have not swollen, are allocated to type G. For coals more strongly swelling than those of type G subscripts are added, e.g. G₁ to G₁₀. These subscripts are determined by the addition of inert material to the coal and are shown in Table 1.

TABLE 1. GRAY-KING COKE TYPES

Coke type	Description
A	Pulverulent.
B	Just coherent, breaks into powder on handling.
C	Coherent, but friable on rubbing.
D	Shrunken, moderately hard.
E	Shrunken and fissured, hard.
F	Slightly shrunken and hard.
G	Hard, occupying same volume as original coal (= "standard coke").
G ₁	Coal; 19 parts — inert carbon; 1 part.
G ₂	" 18 " — " " 2 "
G ₃	" 17 " — " " 3 "
G ₄ and upwards	" 16 " or less — inert carbon; 4 parts or more.

The *swelling properties* are determined by the Crucible Swelling Test described in B.S.1016. Figs. 1 and 2 show examples of the kinds of residue given by these tests. The results of these tests cannot be correlated exactly since the methods used for the tests do not measure precisely the same properties in a coal. Table 2 gives an approximate correlation.

TABLE 2. COMPARISON OF RESULTS OF SWELLING TESTS

B.S. Crucible Swelling Test	0-1	1½	2-2½	3	4-4½	5-5½	6½-7	8	9
Gray-King Assay	A-B	C-D	D-E	D-G	G ₂	G ₃	G ₅	G ₇	G ₈ -G ₁₀

THE EFFECT OF HEAT ON COAL

Knowledge of the mechanism of the decomposition of coal under the action of heat is important whether the coal be used for burning or for carbonization. A brief description is here given of the sequence of events when small pieces of coal, e.g. slack or fines, are heated slowly (say 1-2 deg. C. a minute, as in carbonization practice). The sequence of events, derived from experimental work⁹ on the subject, is shown in Fig. 3.

When a coal crushed into a mass of smaller pieces, e.g. slack or fines, is raised in temperature slowly (say 1-2 deg. C. a minute as in carbonization practice) the sequence of events is that shown in Fig. 3.

No visible change occurs up to about 300° C. (510° F.), but above this temperature the evolution of considerable amounts of oxides of carbon and water vapour shows that the coal is beginning to decompose. If a stream of

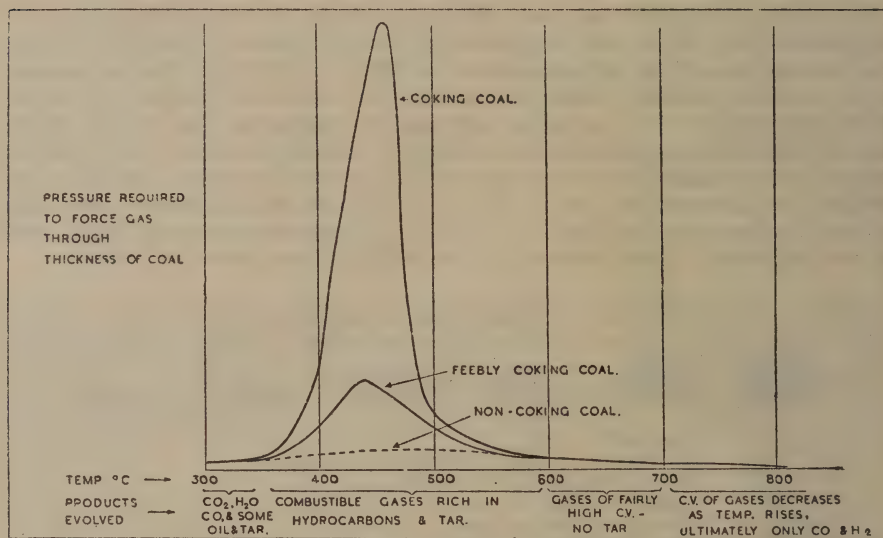


FIG. 3. The behaviour of coal on heating.

inert gas be passed through the heated coal it is found that at about 370° C. (700° F.) a caking coal begins to offer a decided resistance to the passage of gas, whereas a non-caking coal offers little or no such resistance. This is an indication that the coal is beginning to become plastic and that the individual grains are beginning to swell, for the reasons previously described. The temperature at which this commences depends on the rank of the coal and is higher with coals of low volatile content than with coals of high volatile content: the temperature of incipient plasticity may be over 400° C. (750° F.) with a low-volatile coking coal. These effects are shown in Fig. 3, where it will be seen that the pressure required to force gas through coal is negligible for a non-caking coal but may become very high for a strongly-caking coal.

From this temperature of incipient plasticity upwards, the resistance of coal to the passage of gas increases as shown in the figure. The pressure required reaches a maximum and thereupon decreases rapidly as the coal hardens into coke. This maximum occurs at about 430° C. to 450° C. (800° F. to 840° F.) after which, by 500° C., the plastic mass in the case of a caking coal will have hardened into semi-coke. A non-caking coal forms a cellular mass, the grains retaining roughly their original shape. Decomposition is now rapid, gas and tar which may have been imprisoned in the plastic mass are released. The presence of this gas, as has been explained previously, causes a high internal pressure in the plastic coal and the quality of the coke produced from the coal depends to a considerable degree upon this pressure.

Tar continues to be evolved up to a temperature of about 600° C. (1,110° F.) accompanied by considerable quantities of gas rich in hydrocarbons and of a high calorific value. It is during this stage that most of the benzole-forming constituents are evolved from coal; the benzole is not formed as such, but is the product of the secondary decomposition, at a higher temperature, of the primary bodies formed in carbonization.

As the temperature rises to 700°–900° C. (1,290°–1,650° F.) the quantity of gas produced decreases; this gas is of lower calorific value, consisting mainly of carbon monoxide and hydrogen.

For coals with a lower percentage of volatile matter, the temperature range

of plasticity increases. Thus for a coal with 30–35 per cent. volatile matter it may be 370°–450° C. (700°–840° F.), whereas for a coal with 22 per cent. volatile matter, the plastic range may be 420°–530° C. (790°–985° F.). As the coals used become less strongly caking the resistance to the passage of gas during this temperature range becomes less until, with a non-caking coal, there is, of course, no increased resistance since these coals do not pass through a plastic phase.

REPORTING AND INTERPRETATION OF RESULTS OF ANALYSIS

Methods of analysis are dealt with in detail in Chapter 30. The user of coal should, in his own interests, know how results are tabulated and how the different methods are inter-related. Intelligent interpretation of the results of analyses is a valuable aid to the proper understanding of the properties and efficient uses of coals and a knowledgeable fuel user can gain much useful information from the results of an analysis. Even without the addition of such information as sulphur and phosphorus contents, caking power and swelling index, much can be inferred regarding the suitability of any particular fuel for his particular purposes. The industrial user is concerned mainly with the proximate analysis. It is very important to understand how results are expressed and how the different methods of expression are inter-related.

BASES OF REPORTING

The analyst may offer information regarding a coal on any one or more of the following bases:

(a) *As received*. This records total moisture made up of free moisture and inherent moisture, which may be reported separately, volatile matter, fixed carbon and ash. The values for inherent moisture, volatile matter, fixed carbon and ash are calculated from the values obtained on the air-dried coal.

(b) *Air-dried*. The coal is always analysed in this condition. It is ground to pass a 72-mesh B.S. sieve, spread out in a thin layer and allowed to dry until its retained moisture is approximately in equilibrium with the surrounding atmosphere. The analyst then determines the percentages of inherent moisture, volatile matter and ash. The fixed carbon is obtained by deducting the sum of these percentages from 100.

(c) *Dry*. The values for volatile matter, fixed carbon and ash on this basis are obtained by multiplying the values obtained on the air-dried coal by $100/(100-M)$, where M is the determined percentage of inherent moisture.

(d) *Dry, ash-free (d.a.f.)*. The values for volatile matter and fixed carbon on this basis are obtained by multiplying the values obtained on the air-dried coal by $100/[100-(M+A)]$ where M and A are the determined percentages of inherent moisture and ash, respectively.

(e) *Dry, mineral-matter-free (d.m.m.f.)*. The value for volatile matter on this basis is obtained by first deducting from the determined value a correction (p. 9) and then multiplying the result by $100/[100-(M+M.M.)]$ where M is the determined percentage of inherent moisture and M.M. is the mineral matter in the coal. The value for M.M. is obtained by modifying the percentage of ash by the K.M.C. or B.C.U.R.A. formula (see p. 8). This basis gives a lower value for volatile matter than that given by (d); according to the chemical composition of the mineral matter from which the ash is derived. For the purpose of working to this basis, it is, of course, necessary to have the additional information required for applying the K.M.C. formula, information that is seldom available in practice and that concerns the

research scientist rather than the industrialist. Table 3 gives typical results of analyses of two coals.

TABLE 3. RESULTS OF PROXIMATE ANALYSES OF TWO COALS

	COAL I				COAL II			
	<i>Basis of reporting</i>				<i>Basis of reporting</i>			
	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
Free moisture ..	5.0	—	—	—	5.0	—	—	—
Inherent moisture	10.0	10.5	—	—	5.0	5.3	—	—
Total moisture..	15.0		—	—	10.0		—	—
Volatile matter ..	35.0	36.8	41.1	46.6	25.0	26.3	27.8	31.0
Fixed carbon ..	40.0	42.2	47.2	53.4	55.0	57.9	61.1	68.8
Ash	10.0	10.5	11.7	—	10.0	10.5	11.1	—
*Calorific value :								
B.t.u./lb. ..	10,510	11,070	12,370	14,070	12,560	13,220	13,960	15,700

*A calorific value determination is not a part of proximate analysis but the values are inserted here for reference.

Whichever basis is used for recording the results of a Proximate Analysis, the figures given total 100 (per cent.). As a result, the volatile matter content of a coal recorded on one basis is bound to be different from that recorded on any other basis, being, for example, less according to basis (a) than it is according to basis (d).

To extend the table further so as to show the composition of the pure coal substance (dry, mineral-matter-free basis) would involve applying the volatile matter correction and the K.M.C. or B.C.U.R.A. formula, for which the necessary analytical data are not available in the examples given in Table 3; in any case such a statement is of greater interest to the research worker than to the industrial and domestic fuel user to whom this book is mainly addressed.

The first important point to note is that when comparing the figures for two coals the statement on the dry ash-free basis should be given special attention.

The practical significance of the results of proximate (and even ultimate) analysis of coal cannot be ignored by the industrial user. For one purpose the total "inert matter" content (moisture and ash) may be important, for another, the type of coal as judged by (say) the volatile matter in the dry, ash-free coal may be important, and so on. It is not sufficient merely to note how much "dirt" one has to pay for or how much unwanted water. Each "component" making up the balance in a statement of proximate analysis has some significance.

MOISTURE

The total moisture ascertained for the coal "as received" includes the figure for inherent moisture, inseparable (under ordinary conditions) from, and characteristic of, the coal. All the moisture must be driven off by the expenditure of heat when the coal is burnt, of course, but whereas high surface moisture content may be controllable (the coal may not have been sufficiently drained after washing, or may have been exposed to heavy rain in transit or storage) the inherent moisture is due to the specific nature of the coal.

The surface moisture content is important in combustion since a coal that contains fines and is also too dry is likely to lose unburnt dust up the chimney, causing grit and dust emission and resulting in low thermal efficiency. "Wetting" the coal before burning (Chapter 8) is wholly a matter of adding surface moisture.

ASH

For some purposes, or for combustion under some special conditions, the chemical nature of the ash of a coal is significant. A coal of high ash content with a high fusibility may be more satisfactory for some purposes than one of lower ash content but with low fusibility.

GENERAL ASPECTS

When comparing coals on purely commercial considerations, the "as received" figure is specially useful, because it gives the heat units bought and paid for. If, however, some indication is sought as to the character of the coal, the dry, ash-free basis should be used.

Finally it should be noted that none of these tabulated statements records the real composition of the coal. No one knows, as yet, what is the real composition of a coal. Coal certainly does not, for example, contain the volatile matter that is expelled during the analytical process, nor does it contain the ash in the form in which the analyst weighs it, or the boiler operator removes it from the ash pit. These points have already been discussed earlier but can bear repetition.

Fig. 4 (right) shows, in diagrammatic form, the relationships between the results of proximate analysis on the different bases.

- AF represents the composition of the coal as received.
- BF represents the composition of the air-dried coal.
- CF represents the composition of the dry (oven-dried) coal.
- DF represents the composition of the dry, ash-free coal.
- GF represents the composition of the dry, mineral-matter-free coal.
- DG is the K.M.C. or B.C.U.R.A. correction.

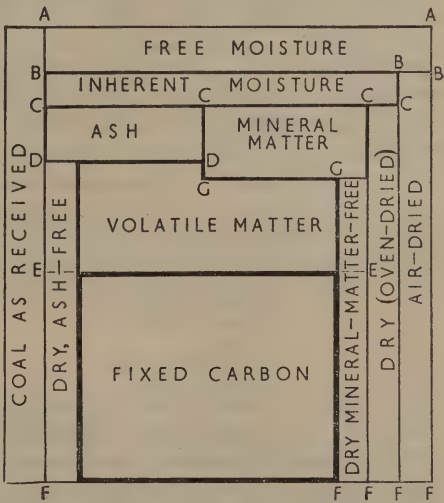


TABLE 4. PROXIMATE ANALYSIS OF FOUR COALS

Basis of analysis	As received				Dry, ash-free (d.a.f.)			
	III	IV	V	VI	III	IV	V	VI
Inherent moisture ..	12.0	2.0	10.0	2.0	—	—	—	—
Ash ..	16.0	7.0	15.0	5.0	—	—	—	—
Volatile matter ..	25.0	25.0	19.0	23.0	34.9	27.5	25.3	24.7
Fixed carbon ..	47.0	66.0	57.0	70.0	65.1	72.5	74.7	75.3

Table 4 further illustrates the differences encountered when reporting results according to the various bases.

Whereas coals III and IV appear, on the "as received" basis, to contain the same percentage of volatile matter they actually belong to different classes. The d.a.-f. analysis figures show that coal III is a medium-volatile coking coal, whereas coal IV is either a high-volatile coking coal or a general purpose coal. This last point could be decided only by a more extensive analysis. On the other hand, comparison of coals V and VI on the d.a.-f. basis show that they belong to the same class—a fact not obvious from the figures on the "as received" basis.

The amount of inherent moisture of a coal is reflected in the volatile matter content, low V.M. values (d.a.-f. basis) being associated with low values for inherent moisture (1–2 per cent.); high V.M. content is associated with higher values for inherent moisture. A coal with 40 per cent. of V.M. (d.a.-f. basis) may have an inherent moisture content of 10 per cent. or more.

If the analytical figures do not support this statement, there is a *prima facie* case for suspecting their accuracy. If the discrepancy is not due to an inaccurate analysis it may be due to the coal being much weathered, or at least more highly oxidised through occurring near the surface; alternatively, it may be due to the heating effects of igneous intrusions.

Proximate analysis is also essential for adequate comparison of different coals that may at first sight appear to be of almost equal thermal value. For example, the calorific values of the coals shown in Table 5 are almost equal and the proximate analysis shows that they are of the same type. The total "inerts" (moisture *plus* ash) content is 22 per cent. in both cases but coal VII has more moisture than coal VIII. If coal VII is fired under a boiler in the "as received" condition the heat evolved has to raise to boiling-point, and then to evaporate, 2.5 per cent. more moisture and further raise the temperature of the water vapour produced. Although, therefore, the ash content of coal VIII is higher, it could be better value than coal VII at the same price per ton.

TABLE 5. PROXIMATE ANALYSES OF TWO COALS OF SIMILAR CALORIFIC VALUE

Coal				VII	VIII
<i>Proximate Analysis :</i>					
Total moisture	..	..		12.5	10.0
Ash	..	..		10.0	12.5
Volatile matter	..	..		25.0	25.5
Fixed carbon	..	..		52.5	52.0
Calorific value, B.t.u./lb.				11,620	11,600

The inherent moisture and volatile matter contents of coal can also be some indication of the caking or coking properties of the coal. For example, a coal with (say) 40 per cent. of V.M. (d.m.-m.-f. basis) and 10 per cent. of inherent moisture will be virtually non-caking and certainly non-coking. The appearance of the "coke button" left behind after a determination of the volatile matter content is a further indication of the caking properties. More accurate methods are those of the Crucible Swelling Number Test and the Gray-King Assay.

TYPES OF SOLID FUELS

The important naturally-occurring solid fuels are: wood, peat, lignite or brown coal, bituminous coal and anthracite. There are other solid fuels, and intermediate varieties of coal not included in this list.

WOOD

Wood is an important domestic fuel throughout the world. By comparison with coal and the liquid and gaseous fuels it is, of course, relatively unimportant. Nevertheless, in certain circumstances it is a useful industrial fuel. Consisting, as it does, mainly of cellulose, which in its chemical composition includes over 43 per cent. of oxygen, it has a low calorific value. The calorific value of absolutely dry wood is of the order of 7,800–9,700 B.t.u./lb. but absolutely dry wood is never available for ordinary use in industry. The value of wood as a fuel lies in its low ash content—0.3–0.6 per cent.—and in the clean long flame that can be obtained from it. In practice it is normally used in the air-dried condition; even then it still contains up to 15 per cent. of moisture, when, of course, the calorific value is still lower. Fresh felled wood may have from 25 to 50 per cent. of moisture.

The specific gravity of most woods being less than 1, as contrasted with that of coal (sp. gr. up to 1.4 or 1.5), it is inconvenient to store it or transport large quantities by rail or road.

The disposal of wood waste is a problem in several industries, especially in the manufacture of furniture. The two main factors in using it as an industrial fuel are obtaining a continuous supply and ensuring that the boilers have sufficient firebox capacity and grate area to suit the fuel. Small quantities of wood waste can be successfully burnt along with coal or coke, provided the firing technique is suitably adjusted. The high volatile matter content makes it necessary to provide about 90 per cent. of the air for combustion as secondary air.

Although stoking and boiler operation, and the principles of combustion of solid fuel are dealt with in other chapters, it is convenient to refer here to the burning of wood. In large installations water-tube boilers using chain grates have been successful; the smaller boiler usually requires a separate combustion chamber or "Dutch oven" built as an extension in which the fixed carbon of the wood may be burnt off. A chamber of this type, having a stepped grate, is illustrated in D.S.I.R. Forest Products Research Laboratory Leaflet No. 41, to which the reader is referred for further information on the subject.

Dust from sanding machines, when mixed with air, becomes highly explosive (cf. coal dust and other industrial dusts); for this reason it should not be burnt unless special precautions are adopted. Wood waste has also been successfully gasified in a gas producer, e.g. to provide the fuel for gas engines at saw mills.

PEAT

Peat differs from the other naturally-occurring solid fuels in that it is a recent growth consisting of partly decomposed vegetable matter resulting from the luxuriant growth of mosses and similar plants under temperate marshy conditions. The lower parts of the stems of the plants die off, but the upper parts continue to grow. The new roots penetrate into the remains of their predecessors mixed, of course, with soil already there and additional soil formed under natural conditions. Thus a deposit of completely decomposed semi-solid material is constantly accumulating.

The amount of water present in these deposits varies greatly, and may be as high as 90 per cent. Near the surface peat is light in colour, but at lower depths it becomes darker, and finally black, when it is not so obviously of vegetable origin. Many peats have a low ash content, but the high water content presents a serious problem and much money has been spent in trying to dry peat on a commercial scale. Peat is a valuable local fuel, extensively used as such in Scotland and Ireland, where it is continually dug out and

dried in stacks during the summer months for use in winter. In some other countries, especially Russia, Finland, Canada, Sweden and Norway, peat is a very important fuel.

LIGNITE AND BROWN COAL

Although lignites have not necessarily been formed under the same conditions as has peat, it is convenient to regard them as intermediate in composition and character between peat and other coals. They are of very great importance in many parts of the world, but lignite occurs only in small pockets in Britain, notably at Bovey Tracey, in Devon. The following varieties are recognized: woody or fibrous brown coal, earthy brown lignite (compact, but friable), brown coal showing cleavage and slight woody structure, black lignite resembling true coal in its appearance. It is interesting to note that the semi-precious stone *jet* is really a hard black lignite.

The lignites are characterized by high moisture content—from 30 per cent. to 50 per cent. They all crumble on weathering and cannot, therefore, be stored for long periods. Lignite may be defined as a solid fuel more mature than peat and showing a definitely woody structure, and brown coal as a still more mature fuel devoid of obviously woody structure, but its vegetable origin can be seen by examination under a microscope. Lignites have a higher moisture content—up to 50 per cent.—and a lower carbon content than brown coals, which have a moisture content of the order of 30 per cent.

Brown coals and lignites are of great importance in the U.S.A., U.S.S.R., Germany, Victoria (Australia), South Australia and India.

The brown coal deposits of Germany are of great economic importance and the mining of brown coal and its utilization as raw fuel, as briquettes and in the carbonization and gasification industries has been very highly developed.

The resources of brown coal in the State of Victoria, Australia, have been estimated at 37,000 million tons; the Morwell brown coal seam has a maximum thickness of 800 feet in one place, with only about 50 feet of overburden. There is also an estimated amount of 226 million tons of brown coal in South Australia. Extensive deposits of lignite and of coals of similar age occur in various areas in India and a "hidden" lignite field has been discovered in recent years in Madras and is now being developed.

'BITUMINOUS' COALS

The term "bituminous" is difficult to define satisfactorily and it would be highly desirable to discontinue its use as a descriptive term in coal technology; attempts to relate it (as applied to coal) to the term "bitumen" lead to confusion, and are not profitable. The term is applied to coals of high and medium volatile matter content; the volatile matter varying from about 45 per cent. down to about 20 per cent., carbon content from under 80 per cent. to about 91 per cent. and hydrogen from about 5.7 to 4.6 per cent.—these amounts being calculated on the basis of dry, mineral-matter-free coal. The inherent moisture contents of bituminous coals vary widely, those containing 80 per cent. of carbon having as much as 15 per cent., while those with 91 per cent. of carbon, the less volatile coals, may contain less than 1 per cent. of moisture.

Examples of bituminous coals, with typical analytical data, are given in Table 6.

TABLE 6. ANALYTICAL DATA FOR 'BITUMINOUS' COALS

Groups or types of coals→ Analytical data	Medium-volatile	High-volatile				
		Very strongly caking	Strongly caking	Medium caking	Weakly caking	Very weakly caking or non-caking
Composition, on dry, mineral-matter-free basis:						
Carbon, per cent.	88.5-91	85-89	84-87	83-86.5	82.5-86	78-85
Hydrogen, per cent.	4.5-5.3	5.1-5.6	5.2 to 5.7			
Volatile matter, per cent. . . .	19.5 to 32	32 to 40		34 to 42		34 to 45
Gross calorific value	{ B.t.u./lb. {	15,600-	15,200-	15,000-	14,800-	14,600-
	{ cal./gm. {	15,900	15,600	15,600	15,400	15,200
		8,670	8,440-	8,330-	8,220-	8,110-
		8,830	8,780	8,670	8,560	8,440
Inherent moisture, per cent. . . .	0.5-2	0.5-2.5	1-4	1.5-5.5	2-10	3.5-18
Gray-King coke type	G ₄ and over	G ₉ and over	G ₈ -G ₆	G ₄ -G ₁	E-G	A-D
B.S. Swelling Number	5-9	6½-9	5½-9	3½-8	1-6	0-4

It will be noted that the calorific value and the percentage of the carbon in the dry, mineral-matter-free coal, as well as the caking and swelling properties, decrease in passing from the first group to the last group of coals. On the other hand the percentages of volatile matter and inherent moisture increase in the same order. Also, as the carbon content decreases the oxygen content increases.

Most industrial coals fall within these groups. There are exceptions; "hards", for example, sometimes cake but they do not swell.

As will be seen from Table 6, the calorific values on the dry, mineral-matter-free basis range from about 15,900 to 13,600 B.t.u./lb.

The Banded Constituents of Coals

Nearly all coals show a laminated structure due to alternating bands of bright and dull coal arranged roughly parallel to the bedding plane. These tend to taper out laterally. They have been classified by Stopes into four types: *vitrain*, *clarain*, *durain* and *fusain*. Without entering into further details here it may be said that vitrain and clarain together constitute the bright bands of coal and durain the dull and harder coal. The bright constituents contain the coke-forming substances. Durain and fusain which contain comparatively little of the bright constituents are, in general, non-caking. As a rule durain has a higher ash content than bright coal from the same seam, but the ash generally fuses at a higher temperature. Fusain is the dull, friable silky-looking material found in thin layers, or in lenticles, along the bedding planes.

A highly specialized science of the petrology of coal has been developed in recent years. The names of the various petrological constituents now applied differ from those originally used and, indeed, do not exactly correspond with them. As most fuel users are not normally concerned with these matters, it is convenient to retain the original names given by Stopes.

Generally speaking, vitrain is the lightest constituent and is characterized by very low ash content and high swelling powers.

The division of a seam into bright and dull coal, when the bands are thick enough to separate them, is often of great industrial importance, since the

two constituents may have appreciably different properties. As an example of this use, the dull coal ("hards") of the East Pennine Coalfield is much favoured for locomotive firing. This is not infrequently due to the high fusion temperature of the ash already referred to.

LOW-VOLATILE 'CARBONACEOUS' COALS*

These are intermediate between bituminous coals and anthracites, their carbon content ranging from about 90 per cent. to about 93 per cent. with volatile matter from about 20 per cent. down to about 9.5 per cent. The hydrogen content varies from about 4.8 to 3.9 per cent. The inherent moisture contents of these *low volatile* coals varies from about 1.5 per cent. to less than 1 per cent. The calorific value varies from about 15,600 to 16,000 B.t.u./lb.

ANTHRACITE*

Coals containing more than about 92 per cent. of carbon and not more than 9.1 per cent. of volatile matter are called *anthracites*. The hydrogen content varies from about 2.8 to 3.9 per cent. and the inherent moisture content from about 1.5 to 3.0 per cent. The calorific value varies from about 15,250 to 15,600 B.t.u./lb. Anthracites have high lustre, sometimes even a graphitic appearance, and although there is banded structure it is not always obvious. Most anthracites occur in the older geological formations, but not all the older coals are anthracites. Many occur in geological formations that have been subjected to folding and compression of the strata; it is in these anthracites that the banded structure is difficult to detect.

OTHER TYPES OF COALS

It is not possible to compile a list of coals in regular linear order of progression of properties, some special coals not fitting into appropriate positions. *Cannel coal* is an interesting example. It is particularly rich in plant remains, and has a very high percentage of volatile matter—as much as 56 per cent.—not to be expected from its other analytical characteristics. It is a dull, hard compact coal with conchoidal fracture and is usually non-caking. It has a high hydrogen content, up to 6.7 per cent. The calorific value may be as high as 15,700 B.t.u./lb. The figures quoted are on the dry, ash-free basis.

In earlier years cannel was used extensively for the manufacture of town gas, giving a gas of high illuminating power. With the advent of the incandescent mantle, gas of high candle-power was no longer necessary, and this use of cannel coal has been discontinued.

THE CLASSIFICATION OF COALS

Many schemes have been devised for classifying coals, schemes based on either proximate or ultimate analysis and mostly with the object of enabling the fuel technologist and the fuel user to assess or predict the properties of a coal, the uses to which it could be put and its behaviour during use. The information already given in Table 6 regarding bituminous coals is in effect such a classification and although it is not comprehensive enough for all purposes yet it provides useful information to guide the coal user as to the properties of the coal he is using. It has already been pointed out that in passing from left to right in that table we see that the percentages of carbon and the calorific value of the coal both fall, the percentages of volatile matter and moisture rising in the same order. There is also a regular progression in the caking properties, which rise to a maximum and then drop off towards the end.

*Analytical figures, except those regarding moisture, relate to dry, mineral-matter-free coal.

Table 7 gives the Gruner-Brame classification for British coals, now, perhaps, of little more than historical interest.

TABLE 7. GRÜNER-BRAME CLASSIFICATION OF BRITISH COALS

No. of class	Name of class	Carbon	Hydrogen	Oxygen	Volatile matter
I	Lignitous	75-80	4.8-5.5	12-20	35-47
II	Ligno-bituminous	78-84	4.5-6	8-13.5	35-45
III	Bituminous { Long flame, non-caking (steam, etc.)	82-86	5-6	6-12	30-40
IV		82-86	4.5-5.5	5-9	30-40
V		85-89	4.5-5.5	4-7.5	20-30
VI	Semi-bituminous	89-92	4-5	2-4.5	13-20
VII	Semi-anthracite	91-93	3-4.5	3-5	8-13
VIII	Anthracite	over 92.5	below 4	below 3	below 8

THE RANK OF A COAL

The biological and geological processes by which wood and other vegetable material have been converted into lignite and coal have been explained at the beginning of this chapter. The account is sometimes illustrated by compiling a list of solid fuels, beginning with wood and proceeding through the range of lignites and bituminous coals to anthracite, thus compiling an elementary classification of solid fuels. It has already been explained that it is difficult to fit some coals into such a simple "straight-line" classification; in fact attempts to compile such a classification always break down and a two-dimensional system must be used. Nevertheless, the *wood-lignite-coal series* (essentially a geological one) does have some practical value and the position of a coal within it is referred to as the *rank* of the coal. The rank of a coal is the degree of metamorphosis or coalification that the original woody and other vegetable materials have undergone during the geological ages that have passed since they were deposited. Coals that have been produced as a result of having undergone the least change are known as *low rank* coals, the extreme examples being the lignites or brown coals.

In passing from coals of low rank to those of *high rank* the carbon content and the calorific value rise progressively, the hydrogen and volatile matter contents falling. Caking power rises to a maximum, after which it falls off again until anthracites—which are non-caking—are reached.

SEYLER'S CLASSIFICATION OF COALS

The earlier classifications were based on the results of proximate analyses. Ultimate analysis, especially as to hydrogen and carbon contents, throws much additional light on the nature of coals, and the recently developed tests for caking power and swelling already referred to have further aided the development of methods of classification.

Several attempts have been made to predict the properties of a coal solely from analytical data, that of Seyler being the best known of the more ambitious among them. In this classification (devised from analytical data on the dry-ash-free basis) the positions of all coals were plotted in a diagram using the percentages of (a) total carbon and (b) hydrogen as the main parameters. All coals were found to occupy positions within a fairly clearly defined curved band. It was found that all coals with any specified volatile matter content occupied positions along a straight line. Those of another specified volatile matter content occupied positions along another straight line roughly parallel to the first. A series of nearly parallel *isovols* were thus constructed across the diagram. Similarly it was found that coals having any specified calorific value

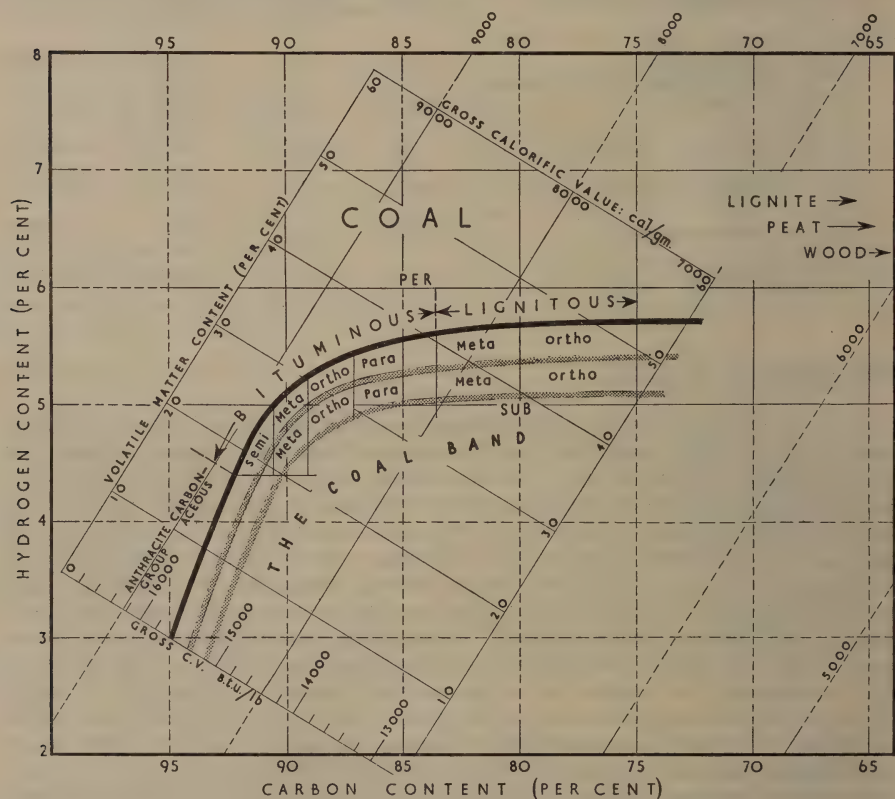


FIG. 5. The Seyler Classification of Coal. Main features.

occupied positions along a straight line and a series of roughly parallel *isocals* could also be constructed across the diagram. The isocals and the isovols were approximately at right angles to each other and inclined to the carbon and hydrogen zero lines or axes. Other properties (caking power) and combustion characteristics can also be shown on the diagram, the simplest features of which are illustrated in Fig. 5.

THE NATIONAL COAL BOARD CODE NUMBER CLASSIFICATION

The practical classification used in British industry is that formulated by the Coal Survey organisation of the Fuel Research Station⁷ and based on the volatile matter content and caking properties. This has been further developed

and modified since the Coal Survey was taken over by the National Coal Board.

As the system was first used in investigations requiring mechanical analysis of the data, numbers were used to designate the different classes of coals; the numerical classification thus evolved has proved in practice to be a useful form of "shorthand" description, and it is now firmly established.

The classification is based on the volatile matter content, expressed on the dry, mineral-matter-free basis, and the caking power of the "clean" coal. For this purpose a clean coal is defined as a coal with not more than 10 per cent. of ash; if the ash content of a coal is more than 10 per cent. it is cleaned by float-and-sink procedure, at the specific gravity that will give the maximum yield of such a clean coal.

Using the volatile matter alone as a criterion, British coals can first be divided into the following main groups:

<i>Group, or general type, of coal</i>	<i>Volatile matter (d.m.m.f. basis)</i>	<i>N.C.B. Code No.</i>
Anthracites	Under 9.1 per cent	100
Low-volatile steam coals ..	9.1-19.5 " "	200
Medium-volatile coals ..	19.6-32 " "	300
High-volatile coals ..	Over 32 " "	400-900 (see below)

In normal coals of the first three groups—i.e. in coals with volatile matter contents of up to 32.0 per cent.—there is in general a close relationship between volatile matter content and caking properties—a matter of much practical significance. Consequently the effect of sub-dividing these groups into progressive ranges of volatile matter content is to produce classes and sub-classes with progressive ranges of caking power also. In the three-figure numbering adopted, the class is indicated by a numeral in the "units" position. These classes and sub-classes are thus numbered 101, 102, 201a, 201b, 202, 203, 204, 301a and 301b. These classes are therefore defined by using the criterion of volatile matter content alone (except in the case of class 301), and the corresponding Gray-King coke types given below in the definitions of the classes are an indication of the ranges found in practice, not criteria for classification.

In the fourth main group—i.e. in coals with volatile matter contents of over 32.0 per cent.—there is a wide range of caking properties at any given volatile matter content, and sub-division has been made on the basis of the Gray-King coke type. Six constituent groups, corresponding to six progressive ranges of caking properties, are recognized:

<i>Group</i>	<i>Gray-King Coke Type</i>	<i>Code Number</i>
Very strongly caking	G ₉ , G ₁₀ and above.	400
Strongly caking	G ₅ , G ₆ , G ₇ and G ₈ .	500
Medium caking	G ₁ , G ₂ , G ₃ and G ₄ .	600
Weakly caking	E, F and G ..	700
Very weakly caking	C and D ..	800
Non-caking	A and B ..	900

Each of the groups 400 to 900 can be further sub-divided according to volatile matter content, the classes being distinguished by a 1 or 2 as the third or units figure of the group code number (e.g. 401 and 402). A figure 1 indicates a class with a volatile matter content of 32.1 to 36.0 per cent.; a figure 2 indicates a class with a volatile matter content of over 36.0 per cent.

Certain coals have been affected by the heat from nearby igneous intrusions, with the result that their caking properties are generally subnormal in comparison with those of unaffected coals of similar volatile matter content. Code numbers 206, 305 and 306 are used to distinguish classes consisting wholly or

TABLE 8. THE COAL CLASSIFICATION SYSTEM USED BY
THE NATIONAL COAL BOARD (*Revised September, 1956*)

Coals with ash of over 10 per cent. must be cleaned before analysis for classification, to give a maximum yield of coal with ash of 10 per cent. or less.

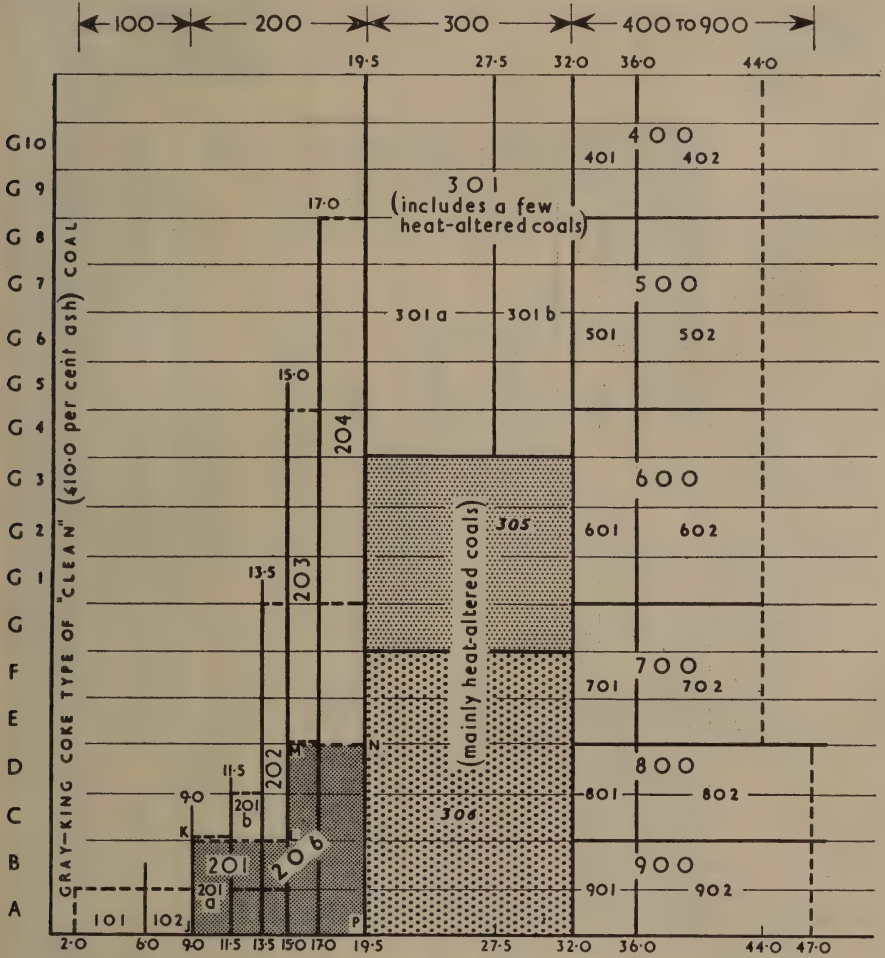
Group(s)	Class	Sub-class	Volatile matter (d.m.m.f.) (per cent.)	Gray-King coke type*	General description
100*	101† 102†		Under 9.1 Under 6.1 6.1-9.0	A do. do.	} Anthracites
200*	201 202 203 204 206	201a 201b	9.1-19.5 9.1-13.5 9.1-11.5 11.6-13.5 13.6-15.0 15.1-17.0 17.1-19.5 9.1-15.0 15.1-19.5	A-G ₈ A-C A-B B-C B-G E-G ₄ G ₁ -G ₈ A-B A-D	Low-volatile steam coals Dry steam coals Coking steam coals Heat-altered, low-volatile steam coals
300	301 305 306	301a 301b	19.6-32.0 19.6-32.0 19.6-27.5 27.6-32.0 19.6-32.0 19.6-32.0	A-G ₉ and over G ₄ and over do. do. G-G ₃ A-F	Medium-volatile coals Prime coking coals (Mainly) heat-altered, medium-volatile coals
400 to 900 400		}	>32.0	A-G ₉ and over	High-volatile coals
	401 402		>32.0 32.1-36.0	G ₉ and over do.	} Very strongly caking coals
500	501 502		>36.0 >32.0 32.1-36.0	do. G ₅ -G ₈ do.	
600	601 602		>36.0 >32.0 32.1-36.0	do. G ₁ -G ₄ do.	} Strongly caking coals
700	701 702		>36.0 >32.0 32.1-36.0	do. E-G do.	
800	801 802		>36.0 >32.0 32.1-36.0	do. C-D do.	} Medium caking coals
900	901 902		>36.0 >32.0 32.1-36.0	do. A-B do.	
			>32.0 32.1-36.0	do. do.	} Weakly caking coals
			>36.0	do.	
			>32.0 32.1-36.0	do. do.	} Very weakly caking coals
			>36.0	do.	
			>32.0 32.1-36.0	A-B do.	} Non-caking coals
			>36.0	do.	

*Coals of groups 100 and 200 are classified by using the parameter of volatile matter alone; the Gray-King coke types quoted for these coals indicate the range found in practice, and are not criteria for classification.

†In order to divide anthracites into two classes, it is sometimes convenient to use a hydrogen content of 3.35 per cent. (d.m.m.f.), instead of a volatile matter content of 6 per cent., as the limiting criterion. In the original Coal Survey rank coding system the anthracites were divided into four classes, then designated 101, 102, 103 and 104. Although the present division into two classes satisfies most requirements it may sometimes be necessary to recognise four or even five classes.

mainly of heat-altered coals. In the volatile matter range 9.1 to 15.0 per cent. there is an overlap between the ranges of Gray-King coke type associated with class 206 and classes 201 and 202.

A full list of code numbers with associated volatile matter contents and caking properties is set out below, in Table 8, and illustrated diagrammatically in Fig. 6.



VOLATILE MATTER Per Cent ON DRY, MINERAL-MATTER-FREE BASIS
Fig. 6. The National Coal Board Code Number Classification of British Coals.

THE E.C.E. INTERNATIONAL COAL CLASSIFICATION

For some years the Classification Working Party of the Coal Committee of the Economic Commission for Europe has been working out systems for the classification of coal for both scientific and industrial purposes. The system so far developed has now reached the stage at which it is possible to publish the principles on which it is based.

It is a two-dimensional scheme, the horizontal parameter being based upon volatile matter content up to 33 per cent. of V.M. and on calorific value for coals with more than 33 per cent. of V.M. on the d.a.f. basis. This parameter

GROUPS (determined by caking properties)			CODE NUMBERS										SUB-GROUPS (determined by caking properties)																																																																													
GROUP NUM- BER	ALTERNATIVE GROUP PARAMETERS		The first figure of the code number indicates the class of the coal, determined by volatile matter content up to 33% V.M. and by calorific value above 33% V.M. The second figure indicates the group of coal, determined by caking properties. The third figure indicates the sub-group, determined by caking properties.										SUB- GROUP NUM- BER	ALTERNATIVE SUB-GROUP PARAMETERS																																																																												
	Free Swelling Index	Roga Index												Dilatometer test : % dilat'n	Gray-King Assay : coke type																																																																											
3	> 4	>45	<table><tr><td rowspan="3">334</td><td>435</td><td>535</td><td>635</td><td rowspan="3">VC</td></tr><tr><td>434</td><td>534</td><td>634</td></tr><tr><td>333</td><td>533</td><td>633</td><td rowspan="3">VD</td></tr><tr><td rowspan="3">332</td><td>432</td><td>532</td><td>632</td><td rowspan="3">733</td></tr><tr><td>332a</td><td>532a</td><td>632a</td></tr><tr><td>332b</td><td>532b</td><td>632b</td></tr><tr><td rowspan="3">323</td><td>423</td><td>523</td><td>623</td><td rowspan="3">VIA</td></tr><tr><td>322</td><td>522</td><td>622</td><td rowspan="3">723</td></tr><tr><td>321</td><td>521</td><td>621</td><td rowspan="3">721</td></tr><tr><td rowspan="3">312</td><td>412</td><td>512</td><td>612</td><td rowspan="3">VIB</td></tr><tr><td>311</td><td>511</td><td>611</td><td rowspan="3">712</td></tr><tr><td>310</td><td>510</td><td>610</td><td rowspan="3">711</td></tr><tr><td rowspan="3">303</td><td>403</td><td>503</td><td>603</td><td rowspan="3">VII</td></tr><tr><td>302</td><td>502</td><td>602</td><td rowspan="3">703</td></tr><tr><td>301</td><td>501</td><td>601</td><td rowspan="3">701</td></tr><tr><td rowspan="3">203</td><td>403</td><td>503</td><td>603</td><td rowspan="3">VIII</td></tr><tr><td>202</td><td>502</td><td>602</td><td rowspan="3">702</td></tr><tr><td>201</td><td>501</td><td>601</td><td rowspan="3">700</td></tr></table>										334	435	535	635	VC	434	534	634	333	533	633	VD	332	432	532	632	733	332a	532a	632a	332b	532b	632b	323	423	523	623	VIA	322	522	622	723	321	521	621	721	312	412	512	612	VIB	311	511	611	712	310	510	610	711	303	403	503	603	VII	302	502	602	703	301	501	601	701	203	403	503	603	VIII	202	502	602	702	201	501	601	700	5	> 140	> G 8
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4	> 45												4	50-140	G 5-G 8																																																																											
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2	2½-4	20-45											2	≤ 0	E-G																																																																											
1	1-2	5-20											1	contraction only	B-D																																																																											
0	0-½	0-5											0	non- softening	A																																																																											

As an indication, the following classes have the approximate volatile matter contents shown :
Class 6 33-44%
7 33-44%
8 35-50%
9 42-50%
Class 6 33-41% volatile matter

CLASSES Determined by volatile matter up to 33% V. M. and by calorific value above 33% V. M.									
CLASS PARA- METERS	CLASS NUMBER								
	0	1	2	3	4	5	6	7	9
Volatile matter (d. a. f.)	0-3	3-10 3-6.5 6.5-10	10-14	14-20	20-28	28-33	> 33	> 33	> 33
Calorific value : (gross calorific value, on moist, ash-free basis) (30°C., 97% humidity) cal./g.	—	—	—	—	—	—	> 7750	7200-7750	6100-7200 and less

As an indication, the following classes have the approximate volatile matter contents shown:

Class 6 33-41% volatile matter
7 33-44% " "
8 35-50% " "
9 42-50% " "

NOTES: (i) Where the ash content of a coal is too high for classification, it must be reduced by laboratory float-and-sink method, or other appropriate means. The S.G. selected for the "cut" should allow a maximum yield of coal with 5-10 per cent. of ash.

(ii) Code No. 332 a, <16 per cent. V.M.; Code No. 332 b, >16 per cent. V.M.

(iii) If a combination of caking and caking properties makes it impossible to fit a coal into any sub-group, the same principles are applied in allocating a Code Number. For example, a coal of Class 7, with a Free Swelling Index of 0-½ but a Gray-King Coke Type B-D, should be given the Code No. 701.

FIG. 7. International Classification of Hard Coals, by type
(Econ. Commn. for Europe, Coal Committee Classification Working Party; July, 1956.)

divides the coals into classes from zero to 9. The classes are then divided into groups and sub-groups. The groups are determined according to the caking properties of the coals (by either the Free Swelling Index or the Roga Index), the sub-groups being determined by coking properties (by either the Dilatometer Test or the Gray-King Assay).

Like the N.C.B. Code Number Classification, the International Classification uses three-figure code numbers.

The system, as developed up to April, 1956, is given in the diagram, Fig. 7.

Certain portions of the diagram are partitioned off and allocated numbers I to VII. These are broad industrial groupings.

THE COALFIELDS OF GREAT BRITAIN

Geological evidence suggests that the original vegetable debris was probably laid down in four large tracts, parts of which have since been removed, leaving numerous detached coalfields. The four areas of deposition were as follows:

- (1) Scotland;
- (2) Northumberland, Durham and Cumberland;
- (3) North Wales, Lancashire, Yorkshire and the Midlands;
- (4) South Wales, Forest of Dean, Bristol and Somerset and Kent.

Of the coalfields now known, 26 are contributing to the coal output of Great Britain. The location of these coalfields is shown in the map appearing as Fig. 8. The exposed coalfields, i.e. those regions where coal measures occur at the surface, are shown in black. The concealed coalfields, i.e. those areas in which coal measures are covered by later rocks but where the coals are within workable distance of the surface, are stippled.

The variation in relative importance of these individual coalfields is very great. Three-quarters of Britain's coal production comes from only six coalfields—Yorkshire, Nottinghamshire and North Derbyshire, Durham, South Wales, Lancashire and Northumberland—the first four of these contributing more than 60 per cent. of the national output.

Nearly all the Scottish coalfields contain many economically important coals in rocks of Lower Carboniferous age (the Limestone Coal Group) as well as in Upper Carboniferous strata (the Productive Coal Measures). In the other coalfields of Great Britain, all or most of the workable coal seams occur in the Upper Carboniferous.

In the Fife and Clackmannan Coalfields, which are one geologically, the strata are folded in the form of a syncline or trough in the East Fife region, as also in Clackmannan and West Fife. These two regions are separated by a complex area of anticlinal (arch-shaped) folding. Faults are numerous. As a consequence of the geological structure, the Productive Coal Measures are practically absent from Central Fife but cover a wide area in East Fife and are also of considerable importance in West Fife and Clackmannan. Seams of the Limestone Coal Group are of importance in all these areas, being yet unworked in the Clackmannan Coalfield. There are undersea workings extending from East Fife, and it is highly probable that the Fife Coalfield extends continuously beneath the Firth of Forth to join the Lothians Coalfield.

The structure of the Lothians Coalfield consists essentially of a syncline, no doubt continuous with that of East Fife. There are two sets of major faults. Seams are worked in the Limestone Coal Group and the Productive Coal measures. There are undersea workings in the Firth of Forth.

The Central Coalfield of Scotland is continuous under the Firth of Forth with the Fife and Clackmannan Coalfields, and also connects with the latter east-north-east of Stirling. The Limestone Coal Group contains a good develop-

ment of seams in the Stirling-Denny and Kilsyth-Barrhead areas, and along parts of the eastern margin of the coalfield; but over a large central region of the coalfield, where Millstone Grit and Productive Coal Measures also occur, the coals of the Limestone Group are of little or no economic significance. Workings have extended beneath the Firth of Forth in the Bo'ness area. The more valuable of the Productive Measures seams have been extensively worked and are approaching exhaustion.

The Ayrshire Coalfield has been affected to a very considerable extent by faulting and folding and by igneous intrusions. In North and Central Ayrshire workable seams occur in the Productive Coal Measures and the Limestone Coal Group, but only the latter group is represented in the isolated South Ayrshire (Dailly) field. The Central Ayrshire field is by far the most important, the greater part of the Ayrshire output coming from this region. In the deep Mauchline basin, which lies within this field, the measures are concealed beneath newer rocks.

In the small Dumfriesshire (Sanquhar) Coalfield only the Productive Coal Measures are present.

Seams in both the Limestone Coal Group and the Productive Coal Measures are worked in the small Douglas Coalfield, which occupies a highly-faulted basin.

In the tiny Campbeltown (Macrihanish) Coalfield the present output comes entirely from one seam in the Limestone Coal Group, but other workable seams occur in this group and in the Productive Coal Measures.

The small Canonbie Coalfield is partly concealed. The exposed portion of the field is intensely faulted. The field is not in production at present, but contains workable seams in the Productive Coal Measures. The Limestone Coal Group seams do not appear to be of economic significance.

Geologically, the Northumberland and Durham Coalfields constitute a single coalfield, responsible for about 20 per cent. of Britain's coal production. Structurally, it appears to consist of a large syncline with an axis running approximately N.-S. in proximity to the coastline, and the eastern limb extending undersea for an unknown distance. The measures usually dip gently. In Northumberland generally, faulting and folding is not intense, although some of the faults have throws of several hundred feet; in Durham faults are quite numerous but usually small. In most of the East Durham region the coalfield is concealed beneath a cover of Permian rocks. There are coal seams in the Lower Carboniferous beds, some of which are worked in Northumberland, but these are of very little economic importance in comparison with the Upper Carboniferous coals, from which nearly 99 per cent. of the present combined output of Northumberland and Durham is derived. Much of the good coal has been worked out in West Durham, the remaining reserves being mostly in thin seams. This applies especially to the central and northern sectors of this region, which have gained fame as sources of high-quality coking coal. Although coal has been mined undersea from coastal collieries of both Northumberland and Durham, it seems likely that there are still considerable reserves of economically workable coal to the east of existing workings, especially in the case of Durham.

The Cumberland Coalfield flanks the north-western margin of the Lake District. The measures have a general gentle seaward dip and a considerable undersea extension, having been worked at one colliery to a distance of more than three miles from the coast. Faulting and folding are frequently encountered in this coalfield; there are two main sets of faults, which often cause large displacements. The northern and southern extremities of the field are concealed.

The Yorkshire and Nottinghamshire and North Derbyshire Coalfields form one geological entity which provides about 40 per cent. of the total output of coal in Britain. With the Millstone Grit of the Pennines as their western margin, the measures in general dip eastwards at low angles, and are concealed beneath a cover of newer rocks in the eastern portion of the field. It is known that the concealed part of the field is of considerable extent, and its eastern margin is as yet undetermined, although it may lie beyond the easterly limits which the depth factor sets to the field from the viewpoint of mining possibilities. The field is bounded to the north by the Millstone Grit outcrop; the southern boundary of the concealed region probably runs a few miles to the south of Nottingham. The strata, particularly in Nottinghamshire and North Derbyshire, have remained fairly free from disturbance. A number of gentle anticlines occur and there are two groups of faults, one set running roughly parallel to the fold axes, the other at right angles to these. In the exposed section of the field there has been a considerable depletion of coal reserves in the region north of Barnsley, where much of the remaining coal is in thin seams, and also in parts of North Derbyshire, but in the recently developed areas of the concealed portion of the field, mining activity has been practically confined to one major seam (the Barnsley or Top Hard). It is probable that the Yorkshire Coalfield contains the largest reserves of coal in Great Britain; the reserves in Nottinghamshire and North Derbyshire are also very large.

On the other side of the Pennines lies the Lancashire Coalfield, in which the Rossendale Anticline virtually isolates the north-eastern Burnley field from the main coal-bearing region of South Lancashire and East Cheshire. In the Burnley area only the lower seams of the sequence are present. In the main field the general dip of the measures is westwards from the Pennines and southwards from the Rossendale Anticline, at fairly high angles; the deepest mine workings in Great Britain are found in this field. A large fault forms the western boundary of the coalfield, while to the south the measures are concealed by Permian and Triassic rocks. Intense faulting has occurred and large displacements are numerous. There are several faults with throws of over 1,000 ft. The long-worked parts of the exposed coalfield are now largely exhausted.

The main portion of the North Wales Coalfield is situated in Denbighshire, the northern Flintshire portion being almost isolated from it by faulting and folding. In general the measures dip to the east and north-east, extending from Denbighshire below the Triassic rocks of the Cheshire Plain and from Flintshire underneath the Dee estuary, where coal is worked from one colliery. The field is heavily faulted; the faults are usually curved and often cause considerable lateral displacement. Most of the reserves of coal lie in the concealed areas of the coalfield, the exposed parts of which have been extensively worked.

It is extremely probable that the three coalfields of Lancashire, North Wales and North Staffordshire are continuous beneath the newer rocks of Cheshire, but the seams are likely to be too deep for economic mining except on the margins of this basin.

In North Staffordshire, coal is won from the Potteries field and the Cheadle field. The former, which is by far the more important, consists of an asymmetrical syncline with an axis running approximately N.-S. and pitching (dipping) to the south. This syncline is flanked on each side by an anticline. The field is highly faulted, and in general the strata are steeply inclined. The faults fall into two series, the major group including two nearly parallel faults with very large throws, one of which causes a displacement of over 2,000 ft. at one place. The exposed portion of the field is bounded on the west by

faults with a large westerly downthrow, while to the south the measures pass beneath younger rocks. A large number of coal seams are present in this field, the lower seams containing high-quality coking coal in the deeper parts of the syncline. Some of the present mine workings are among the deepest in Great Britain. The Cheadle field lies in a basin to the east of the Potteries field, from which it is separated by an anticline.

The Cannock Chase and South Staffordshire (Dudley) Coalfields are respectively the northern and southern regions into which a continuous area of Coal Measures is divided by the Bentley faults. The whole area is highly faulted and folded, the faults falling into two systems. The measures dip at varying angles. There are so-called boundary faults to the east and to the west. The exposed part of the field, which is surrounded by newer rocks, corresponds roughly with the area between these faults, but in the north-west there is an area of concealed measures east of the boundary fault, and in the south-east the exposed measures extend beyond the boundary fault. In the Cannock Chase Coalfield the strata dip to the west or north-west; workings have been confined to the region between the boundary faults, although recent boring has proved the existence of a comparatively shallow concealed area to the east. Most of the small output of the South Staffordshire Coalfield is now drawn from the concealed areas to the east and west of the boundary faults, the central region being virtually worked out. The Thick Coal of South Staffordshire, 30 ft. thick in places, is the equivalent of several of the Cannock Chase seams.

In the Shropshire Coalfield coal is worked in the Coalbrookdale and Wyre Forest regions, but there is now no production from the Shrewsbury area. The general dip of the measures is to the east. A number of faults and folds are present in the Coalbrookdale field.

The measures of the Warwickshire Coalfield are in the form of a syncline with steeply dipping sides and a pitch towards the south. A subsidiary anticline is present in the centre of the field. There are boundary faults to the west, north and north-east, but otherwise the field is little faulted. In the southern part of the coalfield several seams unite to form the Thick Coal. Washouts are of fairly common occurrence in some seams. The extent of the Coal Measures in the areas outside the boundary faults, and beneath the Triassic rocks which conceal them east of a line running southwards from Bedworth, is at present largely unknown.

The South Derbyshire and Leicestershire Coalfields are connected by an anticline in which only unproductive Lower Coal Measures are present in the exposed portion of the field. The western and southern parts of the South Derbyshire Coalfield, and all but the northernmost portion of the Leicestershire Coalfield, are concealed beneath newer rocks. The dip of the measures is usually fairly gentle. The Leicestershire Coalfield is bounded on the east by a fault; another fault marks the present westward limit of working of the South Derbyshire Coalfield. In the latter coalfield there are a considerable number of minor folds and two sets of faults. Except for a few major lines of fracture, the Leicestershire Coalfield is virtually undisturbed. Local washouts are frequently encountered in some of the seams of these coalfields.

It is possible that the coalfields of North Staffordshire, Shropshire, Cannock Chase and South Staffordshire, Warwickshire and South Derbyshire are all interconnected beneath the cover of newer rocks. A recent boring between Lichfield and Tamworth has encountered workable coal seams, indicating the likelihood that the Cannock Chase and Warwickshire Coalfields are continuous at depth.

The chief feature of the complex structure of the South Wales Coalfield,

which contributes over 10 per cent. of Britain's coal production, is an asymmetrical syncline having an E.-W. axis; the main or eastern portion of this coalfield is in the form of an elliptical basin with the longer axis running from east to west, while the western part of the coalfield consists of a narrow belt of Coal Measures extending from east to west across South Pembrokeshire. Practically no part of the coalfield is concealed beneath newer strata, but there are undersea areas in Swansea, Carmarthen and St. Bride's Bays. In the main basin, to which present workings are confined, the beds dip at moderate angles along the greater part of the northern margin, but they are steeply inclined along the highly disturbed region of the South Crop. Three main systems of faults, many of which are in the form of overthrusts, cross this basin, and a number of subsidiary synclines and anticlines are also present. Much splitting and joining is exhibited by the important seams of this coalfield. Across the basin from north-west to east and south, the coal types exhibit a striking and progressive change in rank from anthracites through steam coals to coking coals and (in the east) high-volatile non-coking coals. The total reserves of the South Wales Coalfield are very large indeed, although many areas, especially in the east of the field, have been extensively worked. There are large untouched areas in the western part of the main basin and along the South Crop.

The small Forest of Dean Coalfield occupies a basin which is completely surrounded by older rocks. From the perimeter of this field the measures dip towards the centre at varying angles, being very steeply inclined along the eastern margin, but within the basin there is a steep anticline running in a N.-S. direction. The folding is accompanied by minor faults. The seams have been extensively worked and no significant reserves now remain.

The strata of the Bristol and Somerset Coalfield are also disposed in a geological basin, but over the greater part of the coalfield they are concealed beneath newer rocks. To the west of the main part of the coalfield there are small, almost detached areas of unworked Coal Measures. An anticline to the east of Bristol subdivides the main field into a northern Gloucestershire portion, which is almost unworked at present, and a southern Somersetshire portion. The coalfield has been subjected to intense earth-movements; in places the measures are steeply inclined and highly contorted, and in certain areas there is frequent overthrusting and overfolding, sometimes causing the inversion of a whole series of beds. There are also faults and folds running approximately at right angles to the E.-W. direction of the overthrusts. A zone of overthrusting divides the Somersetshire part of the field into two sub-basins. Most of the seams in this small coalfield are very thin, some having been worked down to a thickness of 1 ft., but the workable lower seams, which contain the important reserves, are generally slightly thicker than the upper seams.

The Kent Coalfield is completely concealed beneath a considerable thickness of newer strata. Structurally, it consists of a shallow syncline with a N.W.-S.E. axis and pitching at a low angle to the south-east. There is not a great deal of faulting, but some subsidiary gentle folds occur in the deeper part of the syncline. The thickness and structure of the seams of this coalfield exhibit rapid lateral variation. In regard to variation in rank of the coals, the coalfield appears to be a small replica of the main basin of the South Wales Coalfield, except that the increase in rank is towards the south-east instead of the north-west. The presence of true anthracites in the south-east portion of the field awaits final confirmation; the worked areas contain coking and coking steam coals. The coalfield extends undersea to the east and south, but its limits in these directions are unknown.

The possible existence of concealed, and workable, coal-bearing deposits in other areas of England south of the Midlands cannot be discounted. The positions of the coalfields in Britain are shown in the map, Fig. 8 below.



Table 9 shows the areas in Britain where coals of the different types are found ; more detailed statistical information regarding recent production, coalfield by coalfield, is given in Appendix C.

TABLE 9. TYPES OF COAL, BY CODE NUMBER, AND AREAS OF OCCURRENCE IN BRITAIN

General description of coals	Coal Rank Code	Coalfields in which found			Per cent. of 1954 output
		Reserves of principal importance	Reserves of secondary importance	Minor reserves	
Anthracites ..	100	South Wales	Central Scottish	Durham, Fife (unworked), Ayrshire (unworked), very probably Kent	1.7
Dry steam coals	201	South Wales	Kent (unworked)	—	2.3
Coking steam coals	202, 203, 204	South Wales	Kent	—	4.2
Prime coking coals	301	South Wales, Durham	Kent	Bristol and Somerset, Lancashire, Northumberland, Central Scottish, Fife, Yorkshire, North Staffordshire (unworked)	8.4
Very strongly caking coals ..	400	Durham, Yorkshire	Northumberland	Bristol and Somerset, Lancashire, Nottinghamshire and North Derbyshire, North Staffordshire, South Wales, Cumberland (unworked), North Wales (unworked)	4.9
Strongly caking coals	500	Yorkshire, Durham	Northumberland, Lancashire, Nottinghamshire and North Derbyshire	Cumberland, North Staffordshire, North Wales, South Wales, Central Scottish, Bristol and Somerset (unworked)	17.8
Medium caking coals	600	Yorkshire, Nottinghamshire and North Derbyshire, Lancashire	Northumberland	Central Scottish, North Staffordshire, Durham, North Wales, Ayrshire, Forest of Dean, South Wales, Dumfriesshire (Sanquhar), Fife, Douglas, Cumberland (unworked), Shropshire (unworked)	14.1
Weakly caking coals	700	Yorkshire, Nottinghamshire and North Derbyshire, Northumberland	Lancashire, North Staffordshire, Central Scottish	Ayrshire, North Wales, Forest of Dean, Douglas, Dumfriesshire (Sanquhar), Shropshire, South Derbyshire, Lothians, Durham, Fife, Cannock Chase, South Wales, South Staffordshire, Bristol and Somerset (unworked)	16.4
Very weakly caking coals	800	Nottinghamshire and North Derbyshire, Yorkshire, Cannock Chase	Warwickshire, Lancashire, Lothians ..	Northumberland, Fife, Central Scottish, South Derbyshire, Ayrshire, North Staffordshire, South Staffordshire, Douglas, Shropshire, Clackmannan, Dumfriesshire (Sanquhar) (unworked), South Wales (unworked), Forest of Dean (unworked)	19.7
Non-caking coals	900	Nottinghamshire and North Derbyshire, Leicestershire, Fife	Warwickshire, South Derbyshire	Lothians, Clackmannan, Cannock Chase, Central Scottish, Yorkshire, Lancashire, Ayrshire, Campbelltown, South Staffordshire, Northumberland, Douglas, North Staffordshire, Forest of Dean (unworked)	9.4
(Usually) heat-altered coals	206, 305, 306	Durham, Central Scottish, Ayrshire	Fife, South Wales	Clackmannan, Bristol and Somerset	1.1

PREPARATION OF COAL FOR THE MARKET

Coal as mined, called "run-of-mine" or "through" coal, comprises a mixture of sizes from lumps measuring 3 feet long down to the finest dust. It also includes "dirt", or "shale", unavoidably collected from the roof or floor of the seam in the process of mining, or occurring as bands of dirt running through the coal itself. This shale may vary in composition from almost pure stone or shale, containing below 10 per cent. combustible matter, to carbonaceous material which may contain up to 60 per cent. of combustible material.

The expression *shale* is commonly used in this context to designate hard stony matter occurring in coal. It should not be confused with the rock, properly called shale, from some of which oil is obtained by distillation in retorts. (See Chapter 3.)

The coal is brought to the surface in tubs or skips and tipped on to shaking screens which separate the large coal from the small coal. The size of the holes in these screens varies from pit to pit, but generally varies between 3 inches and 8 inches. Material known as large coal, which does not go through the holes in the screen plates, then passes on to picking belts. These are long, slowly-moving bands, on either side of which stand men or boys who pick out the easily recognisable dirt and throw it into pockets leading to the dirt disposal arrangements. The operators also either break any pieces consisting of a lump of dirt adhering to a lump of coal or throw them into other pockets. In the latter case further treatment is given to this mixed material, which is known as "middlings". Freed from its impurities, the large coal is loaded into wagons and is usually sold for domestic or locomotive purposes. The cleanliness of this coal naturally depends upon the keenness and activity of the picking belt staff.

Coal smaller than hand-picked size is generally washed and screened into various sizes, and is then sold for gas-making, for coking or for steam-raising at power stations and industrial plants. In 1927 20 per cent. of British coal output was cleaned mechanically. In 1938 this figure had risen to 45 per cent. and in 1956 to about 60 per cent. The proportion cleaned mechanically was still rising in 1956, the proportion cleaned by hand steadily falling. This is a progressive development, since modern washeries operate at high efficiency in separating coal from dirt, while the human picker's efficiency depends upon his eyesight, alertness and activity, all of which are variable and uncertain. About 20 per cent. of the output was cleaned by hand in 1956, and thus a total of 80 per cent. of all British coal was cleaned by one means or another. The remaining 20 per cent. consisted mainly of small coal used almost entirely for power station work.

COAL CLEANING

The operation of practically every mechanical coal-cleaning process depends on the fact that the specific gravity of the shale or dirt is higher than that of the pure coal. Pure coal usually has a specific gravity lying between 1.25 and 1.45 while that of shale is about 2.4 and of iron pyrites ("brasses") about 5.0. The "middlings" (already described) usually have a specific gravity of 1.45-1.8, but if they are broken they tend to split into lumps of pure coal and "pure" shale. Hence they are generally crushed to release any clean coal which they may contain. Some pieces, however, are homogeneous and no amount of crushing will release any coal.

Wet Cleaning Processes

If a mixture of lumps of coal, middlings and shale is placed in a vertical tube with water, and the tube bumped on a rubber mat for a few minutes, it will be found that a separation has occurred. Shale sinks to the bottom of the

tube, the middlings rest on top of the shale and pure coal eventually finds its way to the top layers. This is roughly what goes on in a wet washing plant of the Baum type, which is shown in Fig. 9—except that the water and coal are pulsated by a different method.

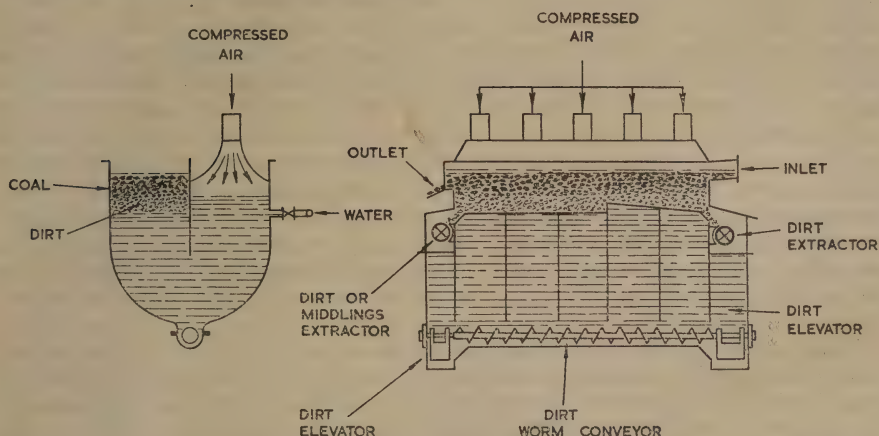


FIG. 9. The Baum Coal Washer

Instead of bumping the container up and down, a pulsating motion of the water is set up by admitting compressed air to the right hand side of the chamber and then releasing it many times per minute, causing the water to move up and down through the perforated bed on which the raw coal travels. This pulsating, up-and-down movement of the water causes the dirt to settle out on the perforated bed-plate while the clean coal rises to the upper layer, as shown in the left-hand diagram. The coal, with a stream of water, travels through the Baum box from right to left (as shown in the right-hand diagram), the clean coal being removed at the left over the vertical weir (marked "OUTLET"); part of the dirt is removed through the dirt extractor on the right hand side, the remainder through the one on the left. Any fine dirt falls through the perforations on the bed-plate and is removed from the bottom of the box by means of the dirt worm conveyor. Sometimes the extractor shown on the right is used for extracting all, or nearly all, the dirt, while that on the left is used to remove middlings, since these settle out below the clean coal in the left-hand portion of the box.

In modern Baum boxes the discharge of the dirt from the perforated bed is controlled by an automatic device. This ensures that the dirt consists almost entirely of shale and that the proportion of coal lost in the dirt is reduced to a very low figure—usually of the order of 1–3 per cent.—depending upon the size of the coal being washed. The loss is usually greater the smaller the coal.

The general tendency now is for Baum boxes to be used for washing coal of 6 in.–0 in size, i.e. for washing all the raw coal which has passed through holes of 6 in. diameter in the screens. The coal larger than 6 in. can be efficiently cleaned by hand since it has been found that the critical size, below which the efficiency of hand-cleaning falls off very rapidly, is 4 in. If the large coal as it comes from the mine is wet, and particularly if it is also coated with fine dirt, it becomes very difficult to distinguish from the dirt, and even more so from middlings. This is particularly the case if there is a lot of soft fireclay next to the coal in the seam. There is a way, however, of separating these three

materials—coal, middlings and shale—with almost perfect efficiency by using a “dense-medium” process.

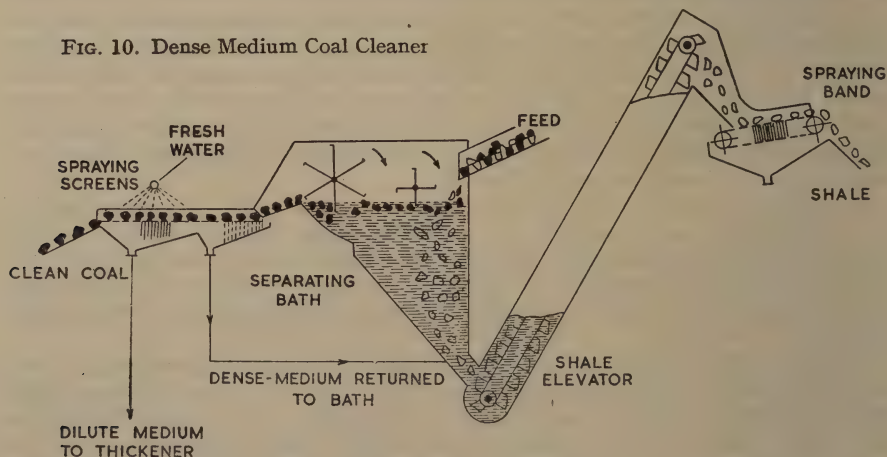
Dense Medium Cleaning Processes

Carbon tetrachloride has a specific gravity of 1.6. It is clear that in this liquid a lump of shale will sink, but lumps of coal and middlings will float. Furthermore, a mixture of carbon tetrachloride and benzene, with a specific gravity of perhaps 1.4, will separate the coal from the middlings since the former will float while the middlings will sink. Thus all the three materials may be separated. This method is used in the laboratory for finding out what are the proportions of good coal, middlings and shale in a raw coal that is to be washed. In practice, however, the liquids mentioned would be both too dear and too poisonous to use. Instead, a “suspension” or “dense-medium” is prepared by fine grinding a suitable solid such as magnetite or barytes and mixing with water. The resulting ‘cream’ or dense-medium can then be used on a large scale in place of the carbon tetrachloride or other liquid used in the laboratory. In one process a suspension of fine river sand in water is used as the dense medium.

The specific gravity of the medium can be adjusted by varying the proportions of magnetite and water and also by varying the fineness of grinding. If one “bath” is filled with dense-medium of specific gravity 1.4, the clean coal can be floated and removed mechanically by rakes or paddles. Middlings and shale will sink and can be dredged out of the bath by means of an elevator with buckets made of perforated plate or by other means. The mixture of middlings and shale can then be passed into a second bath, filled with dense-medium of, say, specific gravity 1.8, in which the shale sinks and the middlings float, the two substances being recovered in the same way as described for the first bath. About a dozen different types of plant are now available, all operating on the same general principle but differing in mechanical construction. Fig. 10 shows a typical arrangement.

These dense-medium plants are generally used for cleaning coal in the size range roughly 8 in. to 1 in.; the middlings are crushed to pass through a 1 in. screen and re-washed in a Baum box along with the raw coal of 1 in.—0 in. size.

FIG. 10. Dense Medium Coal Cleaner



The great advantage of this system of washing is that the only limiting factor in dealing with large coal is the design of the mechanical parts which have to handle the very large pieces. At one plant in Yorkshire, coal as large as 2 ft. in length is being washed by this process. No process of combustion, however, calls for coal as large as this and the modern tendency is therefore to screen

the raw coal on a screen with 8 in. round holes. Coal larger than 8 in. in size then passes to a short inspection belt where very large lumps of shale are removed by hand, together with any pit timber or other material which might damage the machinery. After this inspection the coal is broken to below 8 in. in size and mixed with the raw coal that has passed through the 8 in. holes. This mixture is then washed in two portions, the 8 in.—1 in. in the dense-medium plant, and the 1 in.—0 in the Baum washer, as already described. Instead of choosing 1 in. as the size at which the split is made, $\frac{1}{2}$ in. or even 2 in. may be chosen to suit the characteristics of the coal to be treated.

Dry Cleaning Processes

Coal may also be "dry-cleaned". In a dry-cleaning plant the coal, usually less than 2 in. in size, is passed over a shaking table with a perforated deck through which a current of air blows upwards. This current of air renders the bed of coal "fluid" so that the shale sinks on to the deck while the clean coal rides on top of the shale. The action is similar to that in the Baum washer. By inserting a sort of knife-edge between these two layers, the coal is then separated from the shale. Dry cleaners are not as efficient as wet washers, and in any case their use is dying out rapidly since water is often used underground in cutting the coal in order to prevent dust diseases (for example, pneumoconiosis) amongst miners. Consequently the coal comes to the surface in a wet condition—too wet to permit of its being cleaned by dry methods.

Froth Flotation

One of the results of increased mechanization in the mines has been a considerable increase in the proportion of very fine coal of less than $\frac{1}{50}$ in. in size. Unfortunately, this very fine coal often contains a high percentage of fine dirt and thus also requires cleaning. For this purpose the fine coal, usually mixed with about ten times its weight of water, is passed through a froth flotation plant. Here the fine coal and water are beaten up by an impeller with a "frothing agent"; the impeller also draws air into the system, forming a stream of small bubbles. The effect of the frothing agent, which is usually creosote containing cresylic acid, is to cause the air bubbles to adhere to the particles of coal, but not to the particles of shale. In consequence, the clean, fine coal floats to the surface in the form of a yeast-like scum or froth, while the fine dirt sinks to the bottom of the flotation cell. Clean froth is removed by means of paddles and sent to a vacuum filter, where the bulk of the water is removed, leaving a "filter-cake" of clean, fine coal which is recovered continuously as a crumbly mass containing about 25–30 per cent. of moisture. This filter-cake can be then mixed back with the washed small coal for sale, as its ash content is generally of the order of 5–13 per cent., according to the nature of the coal.

If this very fine coal should prove to be sufficiently low in ash, as is sometimes the case, it is not necessary to use the froth flotation process, which is about three times as costly as the normal processes used for washing larger coal. Instead, the water used in the coal washing plant, containing the fine coal in suspension, is subjected to flocculation. Small quantities of a flocculating agent, such as starch that has been treated with caustic soda, are added to the water. The result is that the minute particles of coal cohere together in the form of "flocs" which settle out much more quickly from the water than would the fine particles themselves. The flocculated slurry is fed into thickeners—large circular tanks with a coned bottom—where the solids settle out rapidly and are pumped to vacuum filters. From the top edge of the thickeners there is an overflow of clarified water which is re-used in the washing process.

THE SIZE OF COALS

In former years, coal, after hand-cleaning and washing, was screened on "classifying screens" into a number of different sizes. The number of different sizes ran into hundreds, and both sizing and nomenclature were in a state of chaos. Sizes were described by names such as *pearls, peas, beans, nuts, bakers' nuts, pears, plums* and other fanciful names. Sizes known as "doubles" in one district were called "singles" in an adjacent district and there was endless confusion. In 1946 a Grading Committee of the British Colliery Owners' Research Association made recommendations for simplifying screening operations and nomenclature. The Grading Committee recommended that seven basic graded sizes of coal should be prepared, viz., Large Cobbles, Cobbles, Trebles, Doubles, Singles, Peas and Grains. The typical sizes for each of these grades were also defined. For example, the typical size of trebles was given as 3 in.-2 in., i.e. coal which had passed through a screen with 3 in. round holes, but was retained on a screen with 2 in. round holes, or the respective equivalents in square holes. It is obvious, however, that if the sizes of holes are specified exactly it would mean that screen plates all over the country would have to be changed in order to comply with the recommendations, since many collieries did not have plates with holes of the specified sizes. At one colliery, for example, the holes for screening trebles might be 3 in. and 2 in., while at another they might be $2\frac{3}{8}$ in. and $1\frac{1}{2}$ in. Accordingly, upper and lower limits were fixed for the sizes of holes used in the classifying screens, which permitted a degree of tolerance to the individual collieries. This would take into account the physical nature of the coal to be screened and marketing requirements. With absolutely fixed sizes it might be found, for example, that too many Trebles were being made while not enough Doubles were available to satisfy the market. By adjusting the sizes within the limits mentioned above, these anomalies could be removed. These recommendations are being implemented by the National Coal Board.

Table 10 gives the Grading Committee's recommendations⁸.

It will be seen that the typical size for Trebles is 3 in.-2 in., but that they *could* have a size range of $3\frac{1}{2}$ in. to $1\frac{1}{2}$ in. by taking into account the permitted limits. $3\frac{1}{2}$ in. is the maximum figure allowed for the upper size limit and $1\frac{1}{2}$ in. the minimum for the lower limit. They could also be of size $3\frac{1}{4}$ in.- $1\frac{3}{4}$ in., for example, since these two figures lie within the ranges of upper and lower size limits respectively.

Where graded sizes are to be used in special combustion appliances such as stoves, their value would be diminished if large proportions of fine coal were present, as would be the case if the screens worked inefficiently. Accordingly, the proportion of "undersize" was also specified in the Recommendations and is clearly shown in the table under the heading "Criteria of undersize".

Quite apart from the graded sizes, of course, a large tonnage of coal is sold as "smalls", i.e. coal having no lower size limit. For example, all the coal passing through a screen with apertures of 1 in. diameter, with no other screen below it, would be described as "*1 in. smalls.*" or 1 in.-0 coal. If the coal is not washed and the screen has round holes, the product would be called "Raw 1 in. round-hole smalls". Similarly washed coal passed through 1 in. square mesh is called "Washed 1 in. square smalls". The term "smalls" should be used to replace the various names previously used, such as "slack", "dant", "duff", "gum", "dross", etc.

GENERAL CONSIDERATIONS

There is a lack of reliable information about the relationship between size, combustion efficiency, or gasification efficiency and draught requirements.

TABLE 10
STANDARD SIZE GROUPS FOR GRADED COALS

Name of group	Typical Screen size (in round hole)	Permitted range of screen apertures (in round hole)*		Criteria of undersize—neither to exceed	
		Upper limit	Lower limit	A †	B †
Large cobbles ..	6 × 3	6 to 8	3 to 5	—	—
Cobbles ..	4 × 2	4 to 5	2 to 3	15% through 1½ in. square	2% through ½ in. square
Trebles ..	3 × 2	2½ to 3½	1½ to 2	25% through ¾ in. square	3% through ⅜ in. square
Doubles ..	2 × 1	1½ to 2¼	1 to 1½	20% through ⅝ in. square	3% through ¼ in. square
Singles ..	1 × ½	1 to 1½	½ to 1	15% through ⅜ in. square	3% through ⅙ in. square
Peas ..	¾ × ¼	¾ to ¾	¾ to ¾	25% through ⅜ in. square	3% through ⅓ in. square
Grains ..	¾ × ¼	¾ to ¾	¾ to ¾	—	—

* Appropriate equivalent square apertures which may be used.

In round hole ..	8	6	5	4	3½	3	2½	2	1½	1	¾	½	⅓	⅓
In square hole ..	7	5½	4½	3½	3	2⅝	2⅝	1⅝	1¼	¾	⅝	⅝	⅝	⅝

† These square meshes refer to those defined in B.S. 410 and are to be used for determination of sieve analyses as required by B.S. 1293.

Note : The Committee expects that the process of evolution of screen sizes will bring them as near as practicable towards the typical sizes.

For gasification the size of coal should be such that the lumps present enough surface for good reaction but are not so small as to prevent easy penetration of air. The same principles apply to combustion, which is most easily achieved with graded coal. It must not be forgotten, however, that the size of particles of the fuel when it is carbonized or partly carbonized may be altered by its caking properties, which may cause particles to cohere.

Proper sizing of coal lessens the rate of segregation. In smalls, which consist of relatively large particles along with fine dust, the larger coal frequently becomes concentrated in one zone of the hopper or heap. As a result, a mechanical stoker fed with such a fuel may at one time be fired with nutty material and at another time with little more than dust. If smalls are supplied to a chain-grate stoker, the sides of the stoker may receive all the nutty material, and the centre the dust. The result is uneven fuel bed resistance and indifferent combustion conditions. Care should be taken to mix the coal thoroughly when wagons of dry smalls are unloaded, since it is usual for the centre of the wagons to contain a greater proportion of fines than the sides or ends. If the centre of the wagon is discharged first, then for several hours the combustion appliance will be using fuel with a high percentage of fines. Later it will receive much coarser material drawn from the ends of the wagon.

Many of these difficulties would be avoided if all the fines could be removed from coal and used in powdered fuel installations, though other counterbalancing difficulties would be introduced. (See Chapter 12.) Unfortunately this objective cannot be achieved at the present time as more fine coal is available than could be absorbed by those industries using powdered fuel. Two influences may help to alleviate this position. Experiments are in progress to develop methods of coal winning which will minimise the production of smalls. Furthermore, the power stations of the future will use more and more pulverized coal for firing their boilers. There is, therefore, good reason to hope for improved coal grading in the future with a consequent general improvement in combustion efficiency.

SELECTION OF COAL FOR MAIN USES

We may now consider the principal characteristics required in coals for their main uses. The aspects considered here apply more particularly to conditions in Britain. The principles governing the methods of selection of coals for industrial and other uses apply in general in any country, subject to modifying factors as regards availability of coals of a particular type, industrial pattern of the country, and so on.

The coals of Great Britain have been classified according to their rank, a system of classification based upon the two important properties of volatile content and coking property, on the dry mineral-matter-free basis and clean coal basis respectively. They have also been classified as to their size in accordance with the nomenclature recommended in the British Colliery Owners' Research Association Report on size grading. These two systems of classification are described earlier in this chapter. The position of any coal in the pattern of rank and size is an indication of certain important properties of the coal and of the uses for which it is suited, subject to certain qualifications relating to the degree of purity of the coal as measured by the content of ash, sulphur, chlorine, etc.

There is, however, another reservation, namely that the best use of the national resources of coal must in the national interest be governed by considerations of availability in relation to demand. British coals have a wide range of quality, and British industry presents an immense diversity

of uses. In the long run the aggregate of consumption must balance the aggregate of supplies; consequently a knowledge of the resources of coal and the significance of the various properties of coals in their uses become specially important, to ensure that all coals may be applied to their best purposes in the national interest.

There is no question that some highly important uses of coal are more selective in their requirements than others. If it is true, therefore, that the coals required, for example, for making coke and gas, for steam-raising in locomotives, for the manufacture of producer gas, etc., must be drawn largely from supplies of certain ranks and sizes and degrees of purity, then it follows that the remainder of available supplies must be directed to uses less selective in respect of coal quality. Of all the main uses of coal, the "residuary legatee" is undoubtedly its use for steam-raising in stationary plant. It is true to say not only that almost any type of coal can be used for steam-raising, but also that it can be used with a reasonable degree of efficiency if attention is paid to the design of the plant and the conditions of combustion. There is here a field for fuel economy no less important to the national interest than the conservation of coals for the more selective uses. In view of the growing demand for coal for carbonization, and the limited availability of the best coking coals, it is now recognized that the better coking coals should be reserved for this purpose.

The following table of "Inland Consumption" is taken from the Reports and Accounts of the National Coal Board for 1955 and 1956:

INLAND CONSUMPTION (52 weeks to 31st December)					
Million tons			Million tons		
1955 1956			1955 1956		
Gas ..	27.9	27.8	Merchants' disposals:		
Electricity ..	42.9	45.6	House coal	29.5	30.6
Coke ovens ..	27.0	29.4	Anthracite and boiler fuel ..	2.0	2.1
Railways ..	12.8	12.8	Other inland consumers ..	18.3	17.4
Iron and steel ..	6.5	6.1	Miners' coal	5.1	5.2
Engineering ..	3.6	3.4	Colliery consumption ..	8.6	7.9
Other industry ..	30.6	29.9			
				214.8	218.2

COKING COALS

In 1955 the consumption of coal in coke ovens was 27 million tons, mostly for the production of blast furnace (i.e. metallurgical) coke. The properties of coke considered most important for metallurgical purposes are:

- (a) resistance to shatter, as judged by the shatter index and the size of the coke;
- (b) ash and sulphur contents;
- (c) phosphorus content in special cases;
- and (d) consistency.

In the range of coals suitable for coking, as the rank of the coal decreases so do the coking properties. The hardest cokes are made from coals of ranks 301 and 401a and normally have 1½ in. shatter indices of 90 or over. In Britain these coals constitute only a small proportion (6.4 per cent. in a recent year) of the total coal output. Our problem, therefore, is to make the best use of these prime coking coals by blending them with the poorer coking coals to produce a satisfactory blast furnace coke. There is no technical difficulty, as it has been repeatedly shown that high class coking coals can "carry" up to 30 per cent. or more of lower rank (i.e. higher volatile) coal in the coke oven and still produce an excellent metallurgical coke. Where transport and economic considerations preclude blending in this way (as in the Midlands and

Scotland) blast furnace coke is made from coals of ranks 500 and 600.

Ideally, the ash content of blast furnace coke should not exceed 10 per cent.; the ash content of the coal charged to ovens should therefore not exceed $6\frac{1}{2}$ – $7\frac{1}{2}$ per cent. These considerations apply to British metallurgical practice. For countries whose coking coals have a much higher ash content, such a specification, would, of course, be quite impracticable. The low sulphur coking coals and the high quality iron ores of India, for example, make an ash content of 15–16 per cent. in the coal quite acceptable for coke oven practice.

The steel industry aims at a stringent limitation of sulphur in blast furnace coke. At present the sulphur content of coal charged to coke oven ranges between 0.9 and 1.7 per cent. Many coals otherwise suitable for coke manufacture cannot be used on account of high sulphur content, except in small quantities in blends. The sulphur content of future resources of coking coal will tend to be somewhat higher than in the past. This problem is not peculiar to Britain.

Coke low in phosphorus content is essential in the production of low-phosphorus pig iron for the manufacture of acid steel. The tonnage of coke so required is small, and careful selection of the coals is usually necessary to provide a coke conforming to a low-phosphorus specification, e.g. not exceeding 0.009 per cent. of phosphorus.

Consistency in blast furnace coke properties has been mentioned as one of the most important requirements in the smooth and economic operation of the iron-making process. Some metallurgical furnace operators, in fact, accord it a very high priority if not, indeed, top place in the list of requirements. The necessary consistency of the quality of the coal charges can be obtained only by cleaning, crushing and blending.

COALS FOR THE GAS INDUSTRY

In 1955 the consumption of coal for gas-making was 27.9 million tons. In gas-making the emphasis has been upon the quantity and quality of the gas produced, but in view of the demand likely to arise as a consequence of the Clean Air Act, the quality of the coke will be increasingly important. Strong coking properties are not so important as in the coking industry. The gas industry uses a wide range of types of coal, but Groups 500 and 600 together account for three-quarters of the total coal used. Outside this range come small amounts of strongly caking coal of Group 400, and a substantial tonnage of the weakly caking group 700 is also used; in Scotland, where there are limited supplies of the higher rank coals, some large and graded coals of class 802 and even 902 are used.

Gasworks practice generally aims at high rates of throughput and high yields of gas as measured in heat units. Both of these are influenced by the caking properties and the size of the coal carbonized. Two-thirds of the supplies are in the form of graded coals (trebles to peas), the remainder being large and unscreened coal. The more strongly swelling coals generally give lower rates of throughput. The trend in the gas industry is towards using larger quantities of the weakly caking coals, groups 600 and 700; coal of groups 800 and 900 can also be used. They give high rates of throughput, without increasing the cost of gas, and though more breeze is produced the coke made is all relatively reactive for the open fire.

Low ash content in gas coal is essential, not merely to attain the highest efficiency of carbonization but mainly because the coke is sold in the domestic market, where it is consumed in small units and operated at comparatively low rates of combustion. As sulphur content is a less serious factor in gas

making, coals outside the sulphur range for the manufacture of blast furnace coke can be used.

The gas industry, making as it does two main products, gas and coke, is a two-fuel industry. The present trends are towards (a) the production of a more reactive coke, especially to facilitate compliance with the provisions of the Clean Air Act, and (b) the adoption of system involving complete gasification.

COAL FOR PRODUCER GAS MANUFACTURE

This use represents an annual consumption of the order of 5 million tons, included in the table given above partly under the heading "Iron and Steel" and partly under "Other Industry" (as, for example, *Glass-works* in the above table). In general, high-volatile, weakly caking coals are used for hot raw producer gas manufacture, and anthracite and coke are used when cold, cleaned gas is required. The highest rates of throughput are obtained with graded coals, notably doubles and singles, of Groups 700 and 800. Although many mechanical producers operate successfully with coals of higher ash content, washed coals with a consistent ash content not exceeding 8 per cent. are preferable. A high ash fusion temperature is desirable, but some control of clinker formation is possible by raising the blast saturation temperature. For most of the purposes to which producer gas is applied, the lower the sulphur content of the coal the better, and a maximum of not more than 1.0 to 1.2 per cent. is preferred.

COAL FOR RAILWAYS

Locomotive coal supplies are drawn from a fairly wide range of ranks in the different coalfields. Essential requirements prescribed by the railway authorities are that the coal shall be large, well screened and free from smalls, that the ash content be low and the ash of a nature that will avoid clinkering difficulties. Electrification and dieselization of the railways will in the course of time reduce the railway demand for large coal.

HOUSE COAL

Supplies are also drawn from a range of ranks according to local circumstances and availability. The best house coals are the larger graded sizes of the higher volatile free-burning ranks, though the demand for the smaller graded sizes is expected to grow. They should be low in ash; ash fusibility is unimportant, for the grate of the ordinary domestic open fireplace should seldom reach a temperature high enough to cause clinkering difficulties. The demand for house coal will ultimately be considerably reduced as a consequence of the implementation of the Clean Air Act.

STEAM RAISING

The requirements for carbonization, for locomotives, for gas producers and for domestic purposes account for an amount approaching half of the total inland consumption; there are, of course, still other uses of coal that are selective in their requirements. It will be seen that, in aggregate, these more selective uses of coal fall heavily upon the large and graded sizes of all coal ranks and upon all sizes of those coal ranks suitable for carbonization. Reference has been made to the use of coal for steam-raising in stationary plant as the "residuary legatee". About half the disposable coal output of the country is so used, and it is clear that in the national interest the bulk of it must be

drawn from coals of ranks unsuitable for carbonization, or from carbonization coals which, for a variety of reasons, e.g. difficulty of cleaning or sulphur content, are unsuitable for that purpose. All British coals must be considered as potentially steam-raising coals, and appliance manufacturers have largely solved the combustion problems set by the wide variety of coal properties. The following paragraphs deal with the effects which the different coal properties have in determining their efficient use for steam-raising.

Rank. Differences in rank are associated with differences in volatile matter content, caking power, calorific value, carbon, hydrogen and inherent moisture content. The lower the V.M. content the more difficult it is to promote and maintain combustion; consequently all effective designs of furnaces for burning the lower-volatile coals include features that ensure high furnace temperatures, and furnace surfaces so placed as to reflect a certain amount of heat on to the fuel bed to keep it at temperatures above the ignition point. High combustion rates are obtained by the use of pre-heated and forced-draught air. The higher-volatile coals are burned more easily, and for medium and small-sized installations sufficiently rapid burning can be obtained by natural draught.

The consumption of coal as pulverized fuel, about 8 million tons per annum at the beginning of the decade, is expected to be more than four times that by the end of it. All types of coal can be burned as pulverized fuel, including anthracite, but when using the lower-volatile coals refractory surfaces, with high combustion chamber temperatures, are essential to maintain ignition; the fineness of grinding and the temperatures of the primary and secondary air are also critical.

High rank in coals implies higher calorific value and lower V.M. content; therefore, another effect of rank that operates in all boilers is that more heat is generated on the grate with the higher-rank coals than with the lower ranks. There is a significant difference between high- and lower-rank coals in the quantity of heat transferred in the various parts of the boiler system, a fact which accounts for the higher gas exit temperatures when using the lower-rank coals.

The relationship between coal rank and calorific value is not a simple linear one, but in general the lower the rank the lower the calorific value. This has two main effects; firstly, there is the lower heat input to the furnace per pound of coal, which partly discounts the higher burning rates with the lower-rank coals; secondly, there is lower calorific intensity. The superb performance of the South Wales semi-bituminous coals, formerly referred to as *Best Admiralty steams*, is largely due to the high calorific intensity, with consequent high radiant-heat transfer, and the high reactivity of the fuel on the bed, all of which features are at a maximum in this range of coals.

When the inherent properties associated with rank are recognised and furnace designs appropriate to the various ranks are adopted, high efficiencies can be obtained with coals of all ranks, other features being favourable.

Size. Large coal is rarely a suitable size for any combustion appliance; it must always be hand-fired, and even in the case of railway locomotives, for which large coal is supplied almost exclusively, it is usually broken before it is used.

In the early days of the development of mechanical stokers, of which the chain-grate is the commonest, sized grades were preferred. Modern developments in the design of mechanical grates, and improvements in the control of combustion, have made it possible to obtain efficient combustion at high rates of burning when using smalls. The need to use sized grades in mechanically-fired boilers has largely disappeared, and is now necessary only when the steam load is greater than can be obtained with smalls.

Three factors associated with the use of smalls have a bearing on the costs of steam production: namely, the carry-over of grit if there is an excessive amount of fines; possible segregation of sizes on the grate with consequent uneven fuel bed conditions and loss of efficiency; and finally certain difficulties which may occur in the coal-handling system resulting in the interference of flow in chutes and bunkers. These difficulties can be overcome by attention to the design and the operation of the plant. Here, as with other properties, consistency in size distribution is desirable.

Moisture. It is necessary to differentiate between the "inherent" and "free" moisture contents. The former increases markedly with decrease in rank; the lowest-rank coals of Britain may contain as much as 15–18 per cent. of inherent moisture. The "free" moisture remaining after drainage is physically entrained during coal getting and washing. The amount in the sized grades is comparatively small, increasing slightly as the size decreases. The "free" moisture content of the washed smalls is unavoidably much higher, the actual amount—which is generally within the range of 5–12 per cent.—depending largely on the amount and nature of the fines content.

The effect of moisture is mainly that of an inert. There are, however, compensating effects. The presence of "free" moisture improves the fuel bed conditions and decreases the resistance to the air largely by attaching the fines to the lump coal. There are noticeable beneficial results from conditioning dry smalls by adding water, and recent work by the British Coal Utilisation Research Association indicates that a certain amount of "free" moisture is necessary to achieve optimum efficiencies. (See Chapter 11.)

Quality and Nature of Ash. As with moisture, the main effect of ash is that of an inert. Certain secondary effects also operate to decrease the effective calorific value, and the amount of coal necessary to generate a given amount of steam is actually greater than would be calculated from the calorific value. These secondary effects, which vary somewhat with the size and the nature of the plant, are more severe in the higher ash content range.

The loss due to unburnt carbon in the ash, the loss of sensible heat in the ashes, and the loss of efficiency in operation as reflected in the greater excess air, all increase with increasing ash content, and this increase is *proportionately* more severe in the higher ash ranges. In hand-fired boilers the effects are probably bigger because of the more frequent cleaning of the fires necessary with the higher ash content coals and the attendant higher losses during the burning-down periods, and afterwards when making up the fire. None of these factors is easy to assess separately.

There are also attendant increased costs when using high-ash coals, which have a bearing on the cost of the steam and in determining the replacement value of coals of different ash content. These added factors are associated with extra labour charges in hand-fired installations, and with additional power and plant costs to handle the extra ash in the bigger mechanically-fired boilers.

The nature of the ash is also important, and perhaps the most important feature is the incidence of clinker formation on the grate and in the furnace. Laboratory determination of the fusion temperature of the ash in an oxidizing or in a semi-reducing atmosphere is not an infallible guide, and there is a need for a more searching and realistic laboratory test. A lower ash fusion temperature can be tolerated with a low-rank coal better than with a high-rank coal because the former gives a lower fuel-bed temperature. Modern boilers with their very high steam temperatures and pressures throw an increasing strain on the fuel, particularly in regard to clinker formation. It would be unwise to look for a solution of the difficulties in a strict seam selection to meet stringent ash fusion temperature specifications. This would

be costly, and would limit the natural and most economic development of the nation's coal resources. It should be realised that a narrow limitation in the range of quality of coals for steam-raising, desirable though it may be on theoretical grounds, cannot be achieved economically on a large scale. High sulphur, phosphorus and chlorine content also affect the behaviour of coals in the bigger modern boilers where the formation of bonded deposits on superheater tubes, economisers and air heaters reduces the period of steaming because of the need to clean the external boiler surfaces. The boiler manufacturers and the bigger users—with the help of the British Coal Utilisation Research Association and the Fuel Research Board—are intensively studying these problems, and it is confidently expected that attention to the design and method of operation and maintenance of the boiler and ancillary plant will overcome the difficulties.

Consistency. It has been said earlier that all the various types, sizes and qualities of coal marketed in this country can be used efficiently for steam raising provided the design of plant and method of operation are satisfactory. While automatic controls (in the case of the bigger plants) and competent firemen (in the case of the smaller hand-fired boilers) can generally take up variations in load without marked changes in efficiency, there is a time lag in adjusting conditions (and consequent loss in efficiency) when the nature or quality of the fuel changes in an unpredictable manner. A very high value can, therefore, be placed on consistency.

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CHAPTER 3

FUELS DERIVED FROM COAL

FUELS derived from coal comprise:

- (a) direct products of carbonization: gas, tar and coke;
- (b) solid and gaseous fuels obtained from the products of carbonization, e.g. producer gas, water gas, blast furnace gas, pitch; and electrode carbon;
- (c) liquid fuels obtained, or by processing the products of carbonization, e.g. oils from the hydrogenation of coal or coal tar fractions, the coal tar fractions themselves, motor benzole, coal tar fuels, and petrol.

The process of carbonization, by which about a quarter of the coal mined annually in Britain is treated, consists in the distillation of coal in closed chambers—coke ovens or retorts—to produce gaseous and liquid products and a solid residue of coke. Coals suitable for coking differ widely in their properties. (See Chapter 2). Those that yield a strong coherent coke on carbonization usually fall within the range of 20–35 per cent. of volatile matter (on a dry, ash-free basis). Those at the upper limit tend to produce weak cokes. Those with 17–20 per cent. tend to swell and produce high pressures, with risk of damage to oven walls; for these reasons, in high temperature ovens they are always used in blends with coals that do not swell, or do not swell so much, and thus do not create such pressure. Those with less than 17 per cent. of volatile matter are classed as non-coking. Coals are blended to avoid setting up unduly high pressure, to secure a particular quality of coke, e.g. blocky, hard or readily combustible, or to produce the best grade of metallurgical coke from the coals that are available. Caking coals with more than 33 per cent. of volatile matter are generally preferred for gas manufacture.

The reserves of good coking coals in Britain and in some other countries, are limited and in danger of becoming exhausted. It is of great importance, therefore, that the best use should be made of these coals, preferably by reserving them for making metallurgical coke either by themselves or after blending them with the maximum possible amounts of other coals. Research is being directed to extending the range of coals that can be used to make coke.

Much work has been done on the production of domestic smokeless briquettes from non-caking or weakly-caking coals. One process, the Phurnacite process, uses finely crushed and dried low-volatile coal (semi-anthracite) briquetted with pitch and then carbonized in inclined ovens. The range of coals suitable for the process is severely limited and research work in progress at the National Coal Board's Coal Research Establishment aims at modifying it so as to apply it to coals of higher volatile content. The capacity of the plant, at present (1956) about 350,000 tons per year, is being increased to produce 600,000 tons of Phurnacite per year. When this capacity has been reached the existing supplies of these special coals will be fully used, and further expansion must depend on the success of research in modifying other coals to make them suitable for the process.

Coal is carbonized in coke ovens, in horizontal or (rarely) inclined retorts, and in intermittent or continuous vertical retorts. A small amount of coal is carbonized at low temperatures (600°C.) for the manufacture of reactive smokeless fuel. The gas-making and coke oven industries each carbonize 25–27 million tons of coal a year, and less than one million tons are used in low temperature carbonization processes. In 1955 the British Gas Industry produced about 523,000 million cu. ft. (250 million therms) of town gas and about 11 million tons of coke for sale and 2½ million tons of breeze.

Coke ovens are located near collieries where coking coal is mined and at places where the coke is required for local use—for example, centres of the iron and steel industry—and they also contribute to the production of gas for the gas industry. In 1955 coke ovens produced about 18 million tons of metallurgical coke and 294,000 million cu. ft. of gas, using 119,000 million cu. ft. of gas for oven heating and supplying 77,000 million cu. ft. to the gas industry, 80,000 million cu. ft. for the metallurgical industries, and 9,500 million cu. ft. to other industries, the remainder being accounted for by domestic use and wastage. In the manufacture of town gas 1,440,000 tons of coke and 526,000 tons (125 million gallons) of oil were gasified. The two industries together produced about 3 million tons of tar, 300,000 tons of ammonium sulphate, 110 million gallons of benzole, and other by-products. The low temperature carbonization industry produces about 480,000 tons of domestic smokeless fuel a year.

Research in progress may, it is hoped, lead to a commercial method of producing town gas from any coal, either caking or non-caking.

THE CARBONIZATION PROCESS

The coal is charged into a closed chamber formed of refractory brickwork, generally of silica. The heating flues are situated in the walls between adjoining chambers, a variation in horizontal retorts being that the heating gases circulate round the retorts. Heat is supplied to the flues by combustion of gas; in coke ovens this is often part of the coal gas produced in the ovens, though producer gas and blast furnace gas are increasingly used, particularly for ovens situated at iron and steel works. Gas retorts are always heated by producer gas made from part of the coke manufactured in the retorts.

The coke remaining in the chamber after the completion of carbonization is discharged and quenched with water. In continuous vertical retorts, and to a lesser extent in intermittent vertical retorts, steam is passed up the retort during all (in the case of continuous retorts) or part (in the case of intermittent retorts) of the carbonization period: this steam reacts with the coke forming *blue water gas* (q.v.) and at the same time cools the coke. Part of the coke is, of course, consumed in the process, and the calorific value of the gas is reduced in proportion to the amount of steam converted into gas. In some plants, the hot coke is discharged into a container and inert gas is circulated through the coke to cool it, the heated gas resulting being circulated through a waste heat boiler to recover the sensible heat of the coke in the form of steam. This is known as *dry quenching*. From 800 to 1,000 lb. of steam can be obtained from a ton of coke in this way. Dry quenching is used particularly in countries such as Switzerland, where coal is costly. It is not commonly practised as yet in Britain.

The gases from carbonization are collected and drawn by *exhausters* through condensers, usually water-cooled, sometimes air-cooled, where ammonia liquor and heavy tars condense. The exhausters pass on the cooled gas, under pressure, through mechanical or electrostatic de-tarriers for removal of the final traces of tar. From this point onwards, the equipment provided depends on whether the *semi-direct* or the *indirect system* of ammonia recovery is practised. In the semi-direct system, the gas is passed direct through diluted sulphuric acid in a saturator, where the ammonia is "fixed" as sulphate of ammonia for use as a fertilizer. In the indirect system, the gas is washed with water, which dissolves the ammonia to produce a weak ammoniacal solution from which the ammonia is recovered by distillation with steam. The ammonia is then either passed into a saturator to produce sulphate of ammonia or condensed to produce crude ammonia solution of upwards of 15 per cent. strength or a purer, stronger solution of 25 per cent. strength.

After ammonia recovery, the cooled gas may be washed with oil to absorb the benzole; this is afterwards recovered as crude benzole by steam distillation of the benzolized oil, and refined to produce motor benzole or pure hydrocarbons (benzene, toluene, etc.). The residual gas is coal gas. Depending on its origin and subsequent use, it is variously styled *coke oven gas* or *town gas*, between which there is no essential difference.

Before coal gas can be used for domestic purposes, i.e. as town gas, hydrogen sulphide must be completely removed; this is done by passing the gas through prepared iron oxide. In due course, the sulphur is recovered from the *spent oxide*. Wet washing processes are sometimes used to remove the bulk of the hydrogen sulphide, purification being completed with iron oxide.

COKE

In the coke oven industry the conditions of carbonization are arranged to give a hard massive coke suitable for metallurgical processes, most of it being used in blast furnaces. Foundry coke is produced from strongly coking coals, of low sulphur content (below 0.9 per cent.), by slow carbonization with comparatively low flue temperatures. Coke made at gas works, often considered to be a by-product of gas manufacture, is made suitable for domestic and other purposes by cutting and grading into suitable sizes, and the small coke is utilized on special grates for steam raising.

The yield of coke from coal varies between 60 per cent. and 80 per cent. of the weight of dry coal carbonized. By weight and thermal value coke is thus the main product of carbonization. It consists of carbon and mineral matter (ash) accompanied by 1-2 per cent. of sulphur, small amounts of volatile matter and still smaller amounts of phosphorus. The method of manufacture of coke influences its properties, but the predominant factor in determining the type and quality of coke is the nature of the coal from which it is produced. At coke ovens the coke available for sale is the amount produced *less breeze* used. At gas works the amount available for sale is much less than the total amount made; a substantial amount, of the order of 2-4 cwt. per ton of coal, is used at the gas works for heating the retorts and further quantities for the manufacture of water gas.

COKE CHARACTERISTICS

The size of coke has an important bearing upon its suitability for use as a fuel, relatively close size-grading being an essential preliminary to marketing. Blast furnace coke should be free from small coke and breeze generally below $1\frac{1}{4}$ in. or (sometimes) $\frac{3}{4}$ in. and should not disintegrate into breeze to any considerable extent during transport to the furnace. Coke suitable for the blast furnace is mostly 2-8 in. in size, but uniformity in size is also important. For other industrial and domestic uses the following size grades have been standardized for coke:

<i>Gas Council limits</i>		<i>B.C.R.A. limits¹</i>	
		<i>Test sieve sizes</i> (inches)	<i>Mean size</i> (inches)
No. 1:	over $1\frac{3}{4}$ in., with no upper limit:	$3\frac{1}{8}$ – $1\frac{3}{8}$	$2\frac{1}{4}$
No. 1A:	within the limits $3\frac{1}{2}$ in.– $1\frac{3}{4}$ in.;		
No. 2:	within the limits 2 in.–1 in.; ..	2– $\frac{7}{8}$	$1\frac{3}{8}$
No. 3:	within the limits 1 in.– $\frac{1}{2}$ in. ..	$1\frac{1}{4}$ – $\frac{1}{8}$	$\frac{7}{8}$
No. 4:	within the limits $\frac{3}{4}$ in.– $\frac{3}{8}$ in. ; ..	$\frac{1}{16}$ – $\frac{3}{8}$	$\frac{5}{8}$
No. 5:	unwashed fuel, approx. $\frac{3}{4}$ in.– $\frac{1}{8}$ in., from which the fines below $\frac{1}{8}$ in. have been removed;	$\frac{1}{2}$ – $\frac{3}{16}$	$\frac{3}{8}$
Breeze generally $\frac{1}{2}$ in.–0			

When used as an industrial boiler fuel, coke needs a low furnace arch to give satisfactory continuity of ignition. 1 lb. of coke of average quality has a net evaporative power of about 9–10 lb. of water from and at 212°F., combustion rates of 12–16 lb. per sq. ft. of grate area per hour can be maintained with natural draught, or 25 lb. with forced or induced draught.

Coke discharged from the retort or oven—other than from continuous vertical retorts, or with dry quenching plants—is quenched by mechanical sprays or by hand in such a way that the bulk of the water is evaporated by the hot coke. If just enough water is used, the residual heat in the centre of the coke drives off practically all the remaining surface moisture. Mechanical means of quenching coke can be more closely controlled than can hand quenching; generally speaking the moisture in pieces over 2 in. can be kept down without much difficulty to below 3 per cent. There is no objection to this amount of water; indeed up to 6 per cent. may be advantageous in that it minimises dust formation. The water content of the smaller “natural” sizes of coke, however, is higher and may be as much as 10 per cent. or even more.

Coke contains very little residual volatile matter, usually not over 4 per cent. whatever the method of manufacture; for gas cokes the range is usually 2–3 per cent., for metallurgical cokes less than 2 per cent.

On account of its porous nature coke has a lower bulk density than that of coal. The apparent specific gravity of coke is obtained by weighing in air and then quickly in water and applying the laws of displacement to the results. The value lies between 0.75 and 1.05. The true specific gravity of coke is determined on coke crushed sufficiently finely to break open all closed pores. The value lies between 1.75 and 2.00. Porosity, which is calculated from the formula:

$$\text{porosity per cent.} = 100 \times \frac{(\text{True S.G.} - \text{Apparent S.G.})}{\text{True S.G.}}$$

varies from 40 per cent. to 60 per cent.

The mechanism of formation of coke from coal and its subsequent quenching with water result in a tendency to form cracks in the coke structure which cause breakage and degradation during handling. This is specially objectionable in blast furnace coke, which must have good resistance to breakage by impact. The impact hardness of coke is measured by the “shatter test”, in which 50 lb. of coke over 2 in. in size is dropped four times from a height of six feet on to a metal plate; a sieve analysis is then made of the resulting broken coke. A good metallurgical coke should show 75 per cent. of the coke over 2 in., 85 per cent. over 1½ in. and less than 3 per cent. below ½ in. size. Gas coke and, more particularly, low temperature coke are “soft” and abradable and usually give a higher percentage below ½ in.

Abradability or surface hardness is determined in the Cochrane Abrasion Test by rotating 28 lb. of coke, sized 2–3 in., in a drum 30 in. diameter by 18 in. long, for 55½ minutes at 18 r.p.m. The product is screened on a ⅛ in. square mesh screen and the percentage remaining on the screen is an index of surface hardness. It is considered that the index is satisfactory if above 74.

ASH IN COKE

A low ash content is desirable in all cokes, whatever the uses to which they are put, but the economics of coal cleaning often place a limit on practical possibilities.

Blast furnace and foundry cokes should preferably contain not more than 10% of ash. Cokes with higher percentages of ash are used in some countries according to the quality of the iron ores making up the blast furnace charge.

The very high quality of many iron ores in India, for example, makes it possible to use the relatively high ash metallurgical coke made in that country.

High ash in domestic coke, particularly if used for open fires, is nearly always objectionable. With such fuel the ash should not exceed 8 per cent. Indeed a lower amount—say, 4–6 per cent.—is desirable. For gas producers an ash with high fusibility temperature is desirable if clinker formation is to be avoided.

Certain British coals are naturally sufficiently low in ash content, or can give very low ash content coal by special cleaning methods, to make the coke produced from them suitable for the manufacture of electrode carbon and other special industrial carbon products, as alternatives to petroleum or pitch coke. The method of cleaning normally adopted for this purpose is froth flotation. Several coals in Britain can be reduced to an ash content of about 0.5 per cent. by this method.

Sulphur is present in coking coals as sulphates, organic sulphur compounds and pyrites (FeS_2). During carbonization, sulphur present as sulphates (which is usually very small) is reduced to sulphides. ‘Organic’ sulphur is partly retained in the coke and partly driven off as hydrogen sulphide, carbon disulphide and other organic compounds. Sulphur present in pyrites becomes converted at about 500°C . into ferrous sulphide (FeS) and hydrogen sulphide (see also Sulphur, Chapter 2.).

The sulphur content of coke lies between 0.75 and 2 per cent. It is a deleterious element for certain purposes, particularly for metallurgical processes or where the products of combustion of coke (or of producer gas made from coke) come into contact with metals affected adversely by sulphur dioxide. About 80 per cent. of the sulphur in coke is released as sulphur dioxide on combustion. The remainder is retained in the ash.

The quantity of phosphorus normally present in metallurgical cokes usually varies between 0.002 per cent. and 0.025 per cent., but it may sometimes be as much as 0.3 per cent. to 0.5 per cent. It is objectionable only when the coke is required for acid pig iron production.

COKE COMBUSTIBILITY

This property, often known as “reactivity” is a measure of the ease of ignition from the cold and of the relative rate of combustion under specified conditions. Metallurgical coke, which is produced at high temperatures from strongly caking coal, is in general less reactive than cokes from the more weakly caking coals or cokes produced at lower temperatures. In general, as the caking power of the coal decreases and conditions of carbonization in respect of time and temperature become less severe, reactivity increases. Temperatures of carbonization as low as 600°C . (*low temperature carbonization*) and relatively low caking power of the coal are the conditions for maximum reactivity; the coke is then very suitable for use in the domestic open fire.

The most reactive oven cokes are made from high volatile, weakly-caking coals such as are found, for example, in Derbyshire and Yorkshire.

An essential property of coke for use in an open grate is that it must ignite readily and burn freely, i.e. it must be reactive. The quality of reactivity is probably best determined by the Critical Air Blast (C.A.B.) test. This is a laboratory test in which is determined the minimum rate of air supply just sufficient to keep a standard bed of 12–35 B.S. mesh coke alight for 20 minutes. When examined by this test typical cokes have C.A.B. values of the following order:

metallurgical cokes	0.05 –0.08
gas cokes	0.05 –0.07
low temperature cokes	0.015–0.025

A low numerical value indicates high reactivity. For use in the open fire low C.A.B. values are desirable, e.g. below 0.035 for the older coal-burning open grate, and below about 0.055 for open grates designed to burn coke as well as coal. No hard-and-fast rule can be prescribed since the behaviour of coke on the open fire is profoundly affected by the size grading used—1 in.–2 in. with the minimum possible amount of over-size being preferred. For closed stoves most cokes are satisfactory.

Cokes having C.A.B. values below 0.050 give easy lighting and maintenance, with ready pick-up in small stoves. Most oven cokes are less reactive than this, values of the order of 0.065 being quite common. In general, the higher the volatile matter of the coke, the lower is its C.A.B. value, i.e. the more reactive it is; but oven operation sets a limit to the amount of volatile matter that can be left in the coke. It should not be inferred, from this statement, that reactivity is simply another measure of relative volatile matter content; highly complex aspects of the structure of the coke are involved.

A practical test of the combustibility of coke other than metallurgical cokes has been developed, using an open grate and a radiometer. The grate is raised above the floor so as to be at the centre of an imaginary hemisphere; the radiation falling on the inside surface of this hemisphere, facing the fire, is measured by thermopiles and can be integrated to a value for total radiant energy. The reactivity of the coke is assessed by:

- (a) the quantity of gas required to ignite the coke—the point of ignition being determined by radiation readings;
- (b) rate of “pick-up” of the fire after ignition;
- (c) maximum rate of radiation observed;
- (d) rate of response in re-fuelling.

Conducted under standard controlled conditions, the test is a valuable practical basis for comparing combustibility of cokes.

Reactivity can be improved by impregnating the coke with small quantities of alkali, provided that the inherent ash is not already strongly alkaline, but this method is not in normal use.

TOWN GAS

Town gas, as distributed by the British Area Gas Boards, has a calorific value between 450 and 500 B.t.u./cu. ft. at 60° F. and 30 in. pressure. The straight coal gas produced by carbonizing a gas coal in a coke oven or gas retort will usually be much richer than this and have a C.V. between 550 and 600 B.t.u./cu. ft. It can be diluted to the required c.v. by mixing it with *producer gas* or *blue water gas* made in a separate plant. Blue water gas is the product of the reaction of steam with red-hot carbon and has a c.v. of 300 B.t.u./cu. ft. If steam is passed into the hot coke at 950–1,200° C. lying in the retort, the coke is cooled and blue water gas is formed. Whilst some water gas can be made in this way in all high temperature carbonizing plants, the horizontal retort and coke oven do not lend themselves to this process and it usually applied to continuous vertical retorts and, to a less extent, to intermittent vertical retorts. Retort gas is therefore a mixture of coal gas with blue water gas, and more rarely with producer gas.

Convenience and economics have combined to popularise another type of gas—*carburetted water gas* (C.W.G.). This is blue water gas enriched by the high-C.V. gaseous products of oil cracked in a separate vessel attached to the water gas plant. The capital charges on the C.W.G. plant are less than on carbonization plant and the plant can be started up at short notice, so that carburetted water gas has a special function in the gas industry as an auxiliary to meet peak loads and sudden demands.

Finally, coal gas produced in high-temperature retorts and ovens contains benzole to the extent of 1 to 5 gallons per ton of coal carbonized. This benzole may be allowed to remain in the gas or it may be wholly or partly removed by washing the gas with creosote oil or a petroleum oil, and recovered in the forms of crude benzole, motor spirit or pure products (benzene, toluene, xylene).

The general characteristics of town gas and of the gases that may be combined to compose it are given in Table 1:

TABLE 1
GENERAL CHARACTERISTICS OF GASEOUS FUELS
Derived from "Technical Data on Fuel"¹².

Type of plant	Composition per cent., by volume					
	Horizontal retorts	Coke oven gas de-benzolized	Steamed continuous vertical retorts	Producer gas from coke	Blue water gas	Carburized water gas
Hydrogen—H ₂	52	54	49.4	11	49	37
Methane—CH ₄ includes ethane, etc.	30	28	20	0.5	0.8	14
Carbon Monoxide—CO ..	8	7.4	18	29	41	30.5
Hydrocarbons—C _n H _m ..	3.6	2.6	2	—	—	7
Carbon dioxide—CO ₂ ..	2	5.2	4	5	4.7	5.6
Oxygen—O ₂	0.4	0.4	0.4	—	—	0.4
Nitrogen—N ₂	4	5.6	6.2	54.5	4.5	5.5
C.V.—gross, B.t.u./cu. ft.	560	525	475	132	295	500
net, B.t.u./cu. ft.	500	467	426	126	270	458
Sp. gr. (air = 1)	0.40	0.38	0.48	0.90	0.55	0.63

The gross C.V. of town gas in Britain is controlled by the Gas Act, 1949, in accordance with which a statutory declaration must be made of the point below which the calorific value of the distributed gas must not fall; this is known as the "declared calorific value". Other statutory obligations are:

- (i) complete absence of hydrogen sulphide;
- (ii) presence of a pungent smell characteristic of coal gas, to act as a warning in case of leakage.

Also in accordance with the 1949 Act, town gas is sold on the basis of heat content, the unit being One Therm—100,000 B.t.u.—measured on the gross C.V.; though gas consumed is generally measured by volume (cubic foot). It is useful to remember that gas of a declared C.V. of 500 B.t.u./cu. ft. is equivalent to 5 therms per 1,000 cu. ft.; similarly gas of 450 B.t.u./cu. ft. is equivalent to 4.5 therms per 1,000 cu. ft. Calorific value may be calculated from the composition of the gas, but somewhat inaccurately because the nature—and hence the calorific value— of the *unsaturated hydrocarbons* depends on the method of manufacture of the gas and the extent to which it has been stripped of benzole before distribution. Accepted values for the constituent gases, saturated with water vapour at 60° F. 30 in. pressure, are as follows:

Hydrogen	H ₂	320 B.t.u./cu. ft.
Carbon Monoxide ..	CO	318 "
Methane	CH ₄	995 "
Ethane	C ₂ H ₆	1,730 "
Ethylene	C ₂ H ₄	1,560 "

Values for the unsaturated hydrocarbons may be taken as 2,365 for horizontal retort gas, 2,300 for coke oven gas, and 2,580 for continuous vertical retort gas. Stripping the gas, i.e. removing the benzole, lowers the calorific value because of the relatively high calorific values of benzene and toluene, which together constitute practically the whole of the product commonly known as *benzole*.

As it comes from the retorts, town gas contains 0.5–1 per cent. by volume (about 300–600 grains/100 cu. ft.) of hydrogen sulphide and smaller amounts of ammonia, hydrocyanic acid, and tar; it is carefully purified so that practically all these are removed before distribution, but the distributed gas still contains a small proportion of organic sulphur compounds—equivalent to 20–35 grains of sulphur per 100 cu. ft. of gas—these consisting of carbon disulphide, carbon oxysulphide, thiophene and mercaptans. If benzole recovery is practised, these are removed to an appreciable extent (40 per cent.) by the *wash oil*, and the distributed gas may contain only 12–20 grains of sulphur per 100 cu. ft. Further reduction of this to 2–5 grains per 100 cu. ft. is technically possible using catalytic methods, but these have not as yet become common practice.

The combustion of town gas is easy to control, highly efficient and easy to apply. Town gas needs no storage capacity at the point of use. The cost of coal gas *on a thermal basis* is higher than that of solid fuels, but its particular characteristics are resulting in its increasing application in industry especially where labour, space, reduction of spoilage and high productivity are important. Its high purity renders it particularly useful for special furnace applications where sulphur would be injurious. The residual organic sulphur compounds can, as already stated, be catalytically removed at the point of use and small-scale desulphurizing plant is available, e.g. in the steel and glass industries, to meet demands for sulphur-free gas.

Shortage of production plant and the incidence of peak demands for gas making inevitably involve variation in combustion properties, but the Gas Industry (in Britain) is moving in the direction of reducing these variations and limiting the time over which they persist. In the meantime, gas burning appliances are made sufficiently flexible to handle these changes in quality. Consequently such variations in combustion characteristics as may occur over a period do not deleteriously affect the use of gas in industry. Town gas is traditionally used mainly for domestic purposes, but the industrial load is steadily increasing. The proportions in which it was used in Britain changed during the period 1947–55 as follows:

	1947 <i>per cent.</i>	1955 <i>per cent.</i>
Domestic	66.4	52.7
Commercial	9.7	15.0
Industrial	19.9	28.8
Street lighting	1.2	1.7
Total sales—million therms ..	2094	2583

PRODUCER GAS

The manufacture of producer gas is described in Chapter 18. It is sufficient here to say that it is manufactured by blowing a mixture of air and steam through a hot bed of coal or coke. The gases leaving the fuel bed consist of a

mixture of carbon monoxide and hydrogen, with some carbon dioxide, and all the nitrogen of the air used in the process; if coal is the fuel used, some hydrocarbons and tar vapour will be present.

The characteristic properties of producer gas depend firstly upon the fuel used and secondly upon whether the gas is used in the hot state or is first cooled and cleaned to remove tar and dust. Typical compositions of cleaned producer gas are given in Table 2.

TABLE 2
COMPOSITION OF CLEANED PRODUCER GAS

Components	Solid Fuel Used		
	Coke	Coal	Anthracite
Carbon monoxide CO	24-28	22-30	25-27
Hydrogen H ₂	11-14	11-16	14-18
Methane CH ₄	0.5	3.0	1.2
Hydrocarbons C _n H _m	—	0.5	0.4
Carbon dioxide CO ₂	4-6	4-6	4-6
Nitrogen N ₂	52-55	52-55	50-53
B.t.u./cu. ft. satd. at 60° F. and 30 in. Hg:			
gross	130-140	140-160	133-155
net	125-135	130-152	126-148
Sp. Gr. (air = 1)	0.9	0.9	0.9

Many types of generator are used for making producer gas. The fuel bed may be deep, hand-clinkered or—more commonly to-day—shallow, mechanically charged and clinkered continuously. It may also be of the hand-clinkered type “built in” to the furnace it serves, in which case the gas passes directly, without cooling, from producer to furnace.

When the fuel gasified is coal there are also produced some gaseous hydrocarbons which increase the calorific value of the gas by some 30 B.t.u. per cu. ft. If the fuel is bituminous coal and the gases are not cooled or cleaned, the additional quantities of tar (*tar fog*) add as much as 15 B.t.u./cu. ft. to the calorific value.

Owing to the high proportion of inert gases (over 55 per cent. of carbon dioxide and nitrogen) producer gas is characterised by a low calorific value and a low flame temperature. It requires only a very small proportion of air for combustion, however, so that a theoretical mixture of gas and air has the fairly high calorific value of 65-72 B.t.u./cu. ft., not very much lower than the value of 92-95 B.t.u./cu. ft. value for a theoretical coal-gas/air mixture. The difference is still less if the producer gas is used hot. For this reason, and because of low unit cost, producer gas has very wide applications as an industrial fuel.

The use of hot producer gas, or of the cooled clean gas, depends on the nature of the furnace operation. Hot gas has the advantage of carrying its sensible heat into the furnace, equivalent to an extra 15 B.t.u./cu. ft. at a temperature of 1,500° F. Clean gas has an obvious advantage in certain types

of furnace operation, though the gas still contains a fairly high proportion of hydrogen sulphide (60–180 grains per 100 cu. ft.).

The applications of producer gas are somewhat limited by its sulphur content, and by its flame intensity. Comparative figures are given in Table 3, which illustrates the main differences between it and the more expensive town gas.

TABLE 3
PRINCIPAL DIFFERENCES BETWEEN PRODUCER GAS AND TOWN GAS

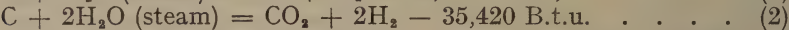
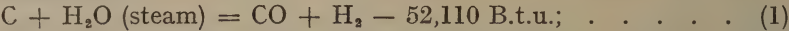
Property	Clean Producer gas	Town Gas
Calorific value: B.t.u. per cu. ft.	130–160	450–520
Flame temperature (cold gas and cold air)	1,600° C.	1,900° C.
Dust: gr./cu. ft.	0·01–0·03	Nil
*oz./1,000 cu. ft.	0·023–0·069	Nil
Sulphur: gr./100 cu. ft.	60–100	20–35
Specific gravity (air = 1)	0·9	0·42–0·48
Hydrogen content, per cent. vol.	10–14	45–55
Air for complete combustion:		
cu. ft. per cu. ft. gas	0·9–1·2	4·25– 4·50
Theor. CO ₂ per cent. in waste gases	19·2–20·5	11·0–13·3
Cal. Value: B.t.u./cu. ft. of theor. air/gas mixture:		
(cold) gross	65–72	95
Ditto net	61–68	85

* 1 oz./1,000 cu. ft. = 0·4375 gr./cu. ft.

Special care must be taken regarding the correct proportion of air to be used with producer gas otherwise combustion may fail. In hot flues this is not so critical, but in all applications a high efficiency in use depends upon ensuring a proper air/gas ratio.

WATER GAS

Water gas is produced by the action of steam on red-hot carbon. The main reactions are:



The amounts of heat shown in the equations are those resulting from the action of steam on one *pound-atom* of carbon, i.e. 12 lb. Carbon exists in several different forms. The figures for the equations relate to carbon in average coke. (See Table 4, Chapter 7). By the action of steam on *graphite* the amounts of heat liberated would be 56,849 and 38,779 B.t.u. respectively. Furthermore, these are the amounts as recalculated to a basis of a final gas temperature of 25° C. the difference between the amounts of heat liberated by the two reactions is constant.

For a fuller discussion of *thermochemical equations* see Chapter 7.

In practice the temperature is kept high in order to favour Reaction (1), but a small amount of carbon dioxide is generally formed, in accordance with Reaction (2). The composition of industrial water gas varies within the following limits:

COMPOSITION OF WATER GAS

Hydrogen	45–51	per cent.
Carbon monoxide	45–40	„
Carbon dioxide.. . . .	3– 6	„
Nitrogen | . . . . .	3– 7	„
Methane	0·1– 0·5	„

The calorific value varies from 290 to 310 B.t.u. (net) per cu. ft.

Water gas burns with a non-luminous bluish flame, for which reason it is commonly called "*blue water gas*." Carburetted water gas (C.W.G.) containing high proportions of hydrocarbon gases burns with a yellowish luminous flame. Water gas is usually made from sized coke, by an intermittent process, in large cylindrical generators. Since the main reaction between coke and steam absorbs a great deal of heat (i.e. is strongly endothermic), the temperature of the fuel bed falls during the production of water gas, and the process of manufacture *must* be intermittent, so as to allow for "blowing" with air in order to raise the temperature again, after which steam is again injected to produce more water gas. In the typical cycle of operations the mass of red-hot coke is "blown" with air, then with steam, the steam being blown first upwards through the coke and then downwards, to distribute the heat uniformly. The whole series of operations occupies from about $2\frac{1}{2}$ minutes to about five minutes, the shorter period being common with automatic operation.

This cycle is repeated, fresh coke being introduced from time to time to maintain the proper depth of the fuel bed, until it proves necessary to remove the ashes and clinker from the generator. In modern plant, the operations are carried out automatically, the valve timing being controlled electrically. Clinker discharge is also made automatic and continuous by the use of a rotating grate. A combustion chamber is sometimes incorporated for burning the "blow" gases, this being followed by a waste-heat boiler to recover the heat thus produced as steam. With such arrangement the thermal efficiency of production may exceed 60 per cent.

For addition to coal gas at the gasworks in the production of a gas for the public supply (town gas) carburetted water gas is manufactured and a second chamber is added in which hydrocarbon oil is gasified. When the water gas has been enriched by the addition of gaseous hydrocarbons in this way, the calorific value may be raised from the original 300 B.t.u. to any desired value up to about 540 B.t.u./cu. ft. At about 500 B.t.u. it will contain 7-8 per cent. of hydrocarbons resulting from the cracking of about 2 gallons of oil per 1,000 cubic feet of carburetted gas.

The main use of water gas is, in the carburetted form, as a constituent of town gas. Blue water gas, however, is of special service in many furnace operations, since the calorific intensity of the water gas flame is high and theoretical flame temperatures of about $1,900^{\circ}\text{C}$. may be reached without pre-heating either air or gas. For furnace heating where the work is intermittent, or where rapid heating is an advantage, water gas is preferable to producer gas. It is, therefore, used—though to a limited extent—in metallurgical process work, particularly steel melting and for special welding. Water gas is used for the synthesis of chemicals such as methyl alcohol, and also as a source of hydrogen for the manufacture of synthetic ammonia, the hydrogenation of oils, etc. This involves the catalytic promotion of the reversible water gas reaction, $\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$ to the right and the removal of the carbon dioxide by washing with water under pressure.

BLAST FURNACE GAS

Blast furnace gas is produced during the production of iron from its ores, and is extensively used as a fuel in the metallurgical industries. Its composition is determined by the composition of the materials charged into the blast furnace and by the furnace operating conditions. Its composition varies considerably within the following approximate limits:

CO_2	.. .. .	8-15	per cent.
CO}	.. .. .	23-33	"
H_2	.. .. .	1.5-3.5	"
Residual nitrogen	.. .. .	50-60	"

The higher the percentage of CO_2 the lower will be the percentage of CO . The calorific value can vary between 80 and 110 B.t.u./cu. ft.; at any one furnace the day-to-day variations are comparatively small.

The gas is similar to a low-grade producer gas, but has a lower hydrogen content. It is suitable, when cleaned, for use in coke ovens, steel works, foundries, etc., for working temperatures up to $1,200\text{--}1,400^\circ\text{C}$. Owing to its low calorific value, however, pre-heating of the gas, or of the combustion air, or of both, is necessary when high working temperatures are needed.

The gas leaving the blast furnace may contain up to 40 grains of dust per cu. ft.; the heavier particles are removed by dust catchers or cyclones. For the most efficient utilization, blast furnace gas must be further cleaned; the final cleaning is usually done by bag filtering or water washing or electrical precipitation, or by one of the first two along with the last-mentioned.

The blast furnace produces about 140,000 cubic feet of gas per ton of coke consumed. The total annual gas production from all blast furnaces in Britain is equivalent to 1,200 million therms. Its full utilization is limited by the difficulty of integrating production and demand, especially at week-ends.

At the larger integrated works the thermal value of the gas represents from a quarter to one-third of the total fuel requirements. Its efficient utilization thus makes an important contribution to fuel economy.

LIQUID FUELS FROM COAL

Liquid fuels can be produced directly from coal by hydrogenation under pressure or indirectly by the production of synthesis gas and the conversion of this synthesis gas, by a catalytic process, to make liquid hydrocarbons (the Fischer-Tropsch process). The hydrogenation process has been commercially used in Britain and both processes were developed on a very large scale in Germany during the 1939–45 war, and have been the subject of large-scale demonstrations in the United States. A full-scale plant has been built, and operated, in South Africa to use the synthesis process. Research and development on various stages of the synthesis process are continuing both in the United Kingdom and abroad. Both processes aim at the complete conversion of coal into motor spirit and hydrocarbon oils. Neither is operated now in Britain, but in one works a large tonnage of creosote is hydrogenated. The use of creosote gives a liquid fuel for internal combustion engines having octane numbers between 90 and 100. It was of particular value during the World War for aviation spirit for fighter aircraft. The advent of the jet engine burning much heavier paraffin oils has made this fuel less essential. During 1954 about 36 million gallons (165,000 tons) of creosote oil were so converted.

COAL TAR FUELS

A number of liquid fuels, and one solid fuel, pitch, are produced by the distillation of coal tar; this chapter deals with their production and characteristics, their uses as fuels being treated in Chapters 12 (Pulverized Fuel) and 13 (Utilization of Liquid Fuels). The amounts utilized annually are of the order of one million tons. In Britain crude coal tar is produced as a by-product of the carbonization of coal in gas retorts and coke ovens; a very small amount (1.4 per cent.) is also produced by processes of low temperature carbonization. The yield of tar from high temperature carbonization is approximately 5 per cent. by weight of the coal carbonized but the amount depends on the nature of the coal and on the process. The production of coal tar in Britain in 1954 was 3.02 million tons, and it is rising; about 63 per cent, is from gas retorts and 37 per cent. from coke ovens. Both types of tar are suitable for the production

of Coal Tar Fuels (C.T.F.), including the extreme end-product, hard pitch, which can be used as a pulverized fuel.

Many valuable products are obtained from coal tar, including phenols, naphthalene, anthracene, oils for creosoting timber, pitch for briquetting, and road tar. Out of 2,778,000 tons of tar distilled in 1955, 662,000 tons went into road tar and 803,000 tons of creosote/pitch mixture and 491,000 tons of pitch were produced.

NOMENCLATURE OF COAL TAR FUELS

It is possible to manufacture coal tar liquid fuels with kinematic viscosities* ranging from 0.1 to 10^{12} stokes at ordinary temperatures (60°F.). The differences in viscosity mean, in practice, that the fuels must be heated to different temperatures in order to ensure that their viscosities at those temperatures are low enough for proper and efficient atomization—0.25 stoke (100 sec. Redwood I). These temperatures, at which all the fuels acquire approximately the same viscosity, are used as the basis for the nomenclature. The fuels are known as C.T.F. 50, C.T.F. 100, C.T.F. 200, C.T.F. 250, C.T.F. 300 and C.T.F. 400 respectively. In order to ensure that each is in a condition suitable for atomization they have to be heated to the temperature indicated, i.e. 50°F. , 100°F. , 200°F. , etc., respectively. (See Chapter 13). The following is an outline of the general characteristics of these Coal Tar Fuels. More detailed information relating to the properties is contained in the handbook published by the Association of Tar Distillers.³ In general, the principles governing the use of coal tar fuels are similar to those for petroleum and shale oil fuels of comparable viscosities.

DERIVATION AND CHARACTERISTICS

The general scheme of tar distillation, including the separation of second-stage products, is given in outline in Fig. 1, with particular emphasis upon the production and composition of coal tar fuels. Medium-soft pitch—C.T.F. 400—

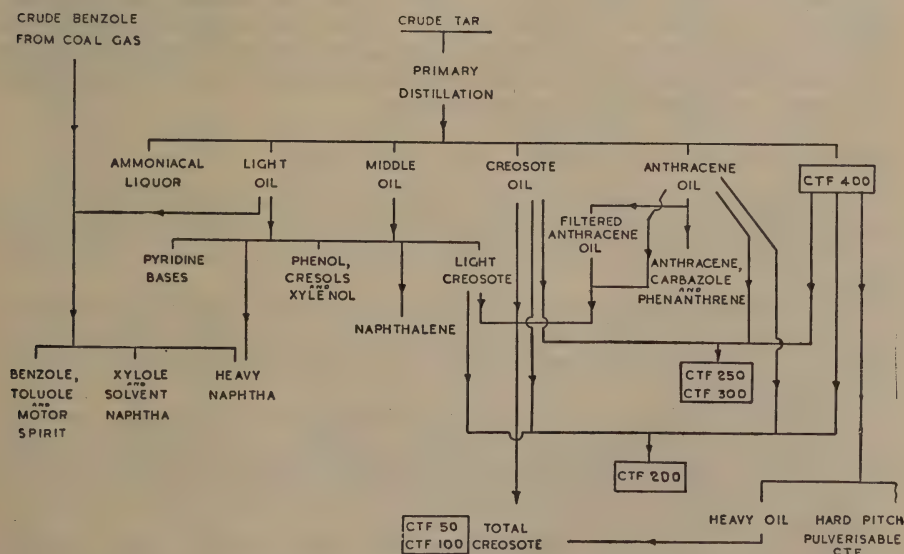


FIG. 1. Scheme of coal tar distillation.

* See Viscosity. Chap. 10 and Chap. 30.

is the normal end-product of tar distillation, and if required for use as a liquid fuel is supplied in loads up to 12 tons in heat-insulated road tank wagons, at a temperature of 300° F. or higher. Deliveries are usually restricted to a radius of a few miles from the tar works. C.T.F. 400 is a black substance, brittle enough at ordinary temperatures to be fractured by a sharp blow. If a Pulverizable Coal Tar Fuel, or hard pitch is required it is necessary to distil off from medium-soft pitch a further proportion of heavy oil until the residue obtained is hard and brittle enough to pulverize readily when cold. It is generally available in lumps ranging from about 18 in. cube downwards, and its application as a fuel is discussed in Chapter 12.

C.T.F. 300 and C.T.F. 250 are prepared either by straight distillation or by diluting—*oiling back*—medium-soft pitch with the heavier tar distillates such as anthracene oil or creosote oil until the required viscosity is attained. At ordinary temperatures they are viscous tarry substances and must be transported hot in heat-insulated road or rail wagons within a limited radius from the works.

Most in demand at the present time is C.T.F. 200, commonly known as Creosote-Pitch Mixture. It is produced by a continuation of the oiling back process, and is a relatively thin, tarry product with a viscosity, at ordinary temperature (60° F.), of about 70 stokes. It can be transported by loading warm into heat-insulated road or rail tank wagons. Where conditions are favourable, large shipments can be made by barge. It has been successfully applied to a large number of industrial plants covering a wide field of production.

C.T.F. 100 and C.T.F. 50 are among the several grades of commercial creosote produced by selective blending of the medium and heavy oil distillates from the primary distillation of crude tar. They are sometimes known as Creosote Grade B and Creosote Grade A respectively, and are frequently used for flushing liquid fuel systems before closing down or before changing over from a petroleum fuel to a coal tar fuel, or *vice versa*. They distil above about 200° C. (390° F.) and contain at least 99·5 per cent. of material soluble in toluole. C.T.F. 50 is fluid down to 32° F. but the amounts available are limited. At atmospheric temperatures, C.T.F. 100 often contains a quantity of separated solids consisting mainly of naphthalene, but at temperatures above 90° F. it is completely fluid. The fluidity temperatures of these two fuels must be borne in mind when arranging deliveries.

GENERAL PROPERTIES OF THE COAL TAR FUELS

In the handbook "Coal Tar Fuels" referred to above³, suitable commercial specifications are given for these fuels; C.T.F.'s 50, 100 and 200 are also covered by B.S.1469—Coal Tar Liquid Fuels⁴. Table 4 lists the most important properties.

When delivered, the coal tar fuels are effectively free from water. With the possible exception of C.T.F. 50, and in contrast with petroleum oils, any extraneous water present, being less dense than the fuel, accumulates on the surface. (See Chapter 13.)

Coal Tar Fuels have a low sulphur content, rarely above 1 per cent. by weight and generally much below that figure. They contain only small quantities of inorganic matter, the amount of ash never exceeding 0·75 per cent. by weight; in the creosotes and the less viscous tarry fuels the ash content is almost negligible.

Among the liquid fuels C.T.F.'s 200, 250, 300 and 400 contain varying amounts of matter insoluble in toluole, the maximum ranging from about 15 per cent. by weight (for C.T.F. 200) to 30 per cent. (for C.T.F. 400). This toluole-insoluble material consists of resinous compounds of high molecular

TABLE 4
PROPERTIES OF COAL TAR FUELS

Item	C.T.F. (a) 50	C.T.F. (a) 100	C.T.F. (a) 200	C.T.F. 250	C.T.F. 300	C.T.F. 400	Pulverizable C.T.F.	Item
1	(c)	1.01	1.13	1.16	1.19	1.23	—	1
2	≥ 60 (100)	≥ 100 (100)	≥ 5,000 (80) ≥ 1,500 (100) ≤ 1,000 (100) ≥ 100 (200)	≥ 5,000 (135) ≥ 1,500 (160) ≥ 100 (250)	—	—	—	2
3	—	—	—	70-120 (30)	40-60 (55)	—	—	3
4	—	—	—	—	36	73-80	≤ 108	4
5	—	—	—	—	—	—	≤ 100	5
6	≥ 1.0	≥ 1.0	—	—	—	—	—	6
7	—	—	≥ 1.0	≥ 0.5	≥ 0.5	≥ 0.5	—	7
8	≥ 0.5	≥ 0.5	≥ 15.0	≥ 23.0	≥ 26.0	≥ 30.0	—	8
9	32° F.	90° F.	—	—	—	—	—	9
10	≤ 150° F.	≤ 150° F.	≤ 150° F.	≤ 150° F.	—	—	—	10
11	0.05	0.05	0.25	0.3	0.3	0.75	0.75	11
12	≤ 16,500 (370)	≤ 16,500 (370)	≤ 16,250 (364)	≤ 16,000 (358)	≤ 16,000 (358)	16,000 approx. (358)	16,000 approx. (358)	12
13	≥ 3.0	≥ 3.0	—	—	—	—	—	13
14	≥ 1.0	≥ 1.0	≥ 1.0	≥ 1.0	≥ 1.0	≥ 1.0	≥ 1.0	14

(a) B.S. 1469 : 1948. (b) to convert into lb./gal. multiply by 10. (c) Varies, depending on the source of the crude tar. Range 1.0 to 1.08
 ≥ : maximum, i.e. not more than. ≤ : minimum, i.e. not less than.

weight containing high percentages of carbon. The particles are of microscopic dimensions, and form a stable uniform dispersion in the oily medium, which does not cause any difficulty if the fuels are kept at the temperatures correct for their proper application. These fuels must never be mixed with petroleum fuels because precipitation generally occurs and renders the mixture unfit for use. When changing over from C.T.F. to petroleum fuels, or vice versa, the whole system must be thoroughly cleaned out before admitting the new fuel. (See Chapter 13, and reference above to Creosote, Grades A and B.)

The calorific value of creosote/pitch mixture, C.T.F.200, on a weight basis, is less than that of heavy petroleum fuel oils by approximately 12 per cent., but on a volume basis it is about 6 per cent. higher because of the difference in specific gravities.

On the basis of specific gravities and calorific values given above it will be seen that the calorific value of coal tar fuels ranges from 167,000 to 197,000 B.t.u. per gallon.

Pulverizable Coal Tar Fuel is probably the nearest approach to an ideal solid fuel that is commercially available. Its special advantages as a fuel are referred to in some detail in Chapter 12.

Typical ultimate analyses of the Coal Tar Fuels are given in Table 5.

TABLE 5
ULTIMATE ANALYSES OF COAL TAR FUELS

	C	H	S	N	O by dif.
	<i>per cent.</i>	<i>per cent.</i>	<i>per cent.</i>	<i>per cent.</i>	<i>per cent.</i>
C.T.F. 100 (a)	89.30	6.90	0.13	0.84	2.83
C.T.F. 100 (b)	86.50	8.00	0.25	0.84	4.41
C.T.F. 200	89.86	6.05	0.39	1.11	2.59
C.T.F. 250	89.97	5.90	0.44	1.16	2.53
C.T.F. 300	90.08	5.73	0.49	1.22	2.48
C.T.F. 400	90.42	5.23	0.65	1.38	2.32
Pulverizable C.T.F.	90.66	4.90	0.86	1.42	2.16

a London Horizontal Retort Tar Oil b Midland Vertical Retort Tar Oil

The change in viscosity with temperature—the *temperature susceptibility*—of a coal tar product is greater than that of a petroleum product of comparable viscosity. Included in the handbook "Coal Tar Fuels" is a nomogram which can be applied with reasonable accuracy to the various makes of liquid coal tar fuels. It provides viscosity data relating to C.T.F.'s 200–400 inclusive, over the temperature range 30–400° F. The viscosities can be expressed in poises, in stokes, or in time of flow (in seconds) from the Redwood No. 1 Viscometer or the standard Tar Viscometer. This nomogram will prove of great help to those required to handle and distribute the more viscous Coal Tar Fuels.

The specific heat of the coal tar fuels throughout their normal working ranges varies between 0.35 and 0.45. Evidence up to date tends to show that the thermal conductivity of coal tar fuels is between 0.08 and 0.085 B.t.u. per sq. ft. hr. deg.F./ft.

The maximum flame temperature obtainable under optimum conditions is over 1,700° C. It has become apparent that coal tar fuels, and particularly the heavier varieties, are pre-eminently suitable for many metallurgical purposes. The flame is intensely luminous; consequently a high rate of heat transfer is possible when heating or melting metals. It has recently been demonstrated by

the Flame Radiation Research Association that for equal heat input the emissivity of the flame of C.T.F. 200 is about 18 per cent. greater than that of similar grades of petroleum oil. This fact emphasizes the value of Coal Tar Fuels for some metallurgical purposes—particularly for use in Open Hearth Steel Furnaces.

In addition to the handbook “Coal Tar Fuels” and B.S.1469, Fuel Efficiency Bulletin No. 36⁵ contains useful information relating to C.T.F. 200 and its application.

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CHAPTER 4

PETROLEUM AND SHALE OIL FUELS

PETROLEUM AND NATURAL GAS

CRUDE PETROLEUM is a liquid, light brown to black in colour and varying very considerably in viscosity, according to origin. It occurs in sedimentary rock strata and is tapped by drilling and subsequent pumping. In the initial stages it may emerge from the bore hole under hydrostatic or gas pressure, the gas exerting this pressure, which also occurs in large accumulations not contiguous to crude oil, being known as *natural gas*.

Natural gas. Natural gas is for the most part methane (CH_4), the first member of the paraffin series of hydrocarbons. A considerable amount of natural gas is expelled from the liquid petroleum, and recovered in the course of its refining. Both in the free natural gas and in the gases dissolved in crude petroleum there are present in addition to methane, but to a lesser extent, ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}) and higher hydrocarbons and small amounts of hydrogen sulphide, carbon dioxide, nitrogen and (in a few cases) helium. Typical analyses of natural gas are given in Table 1.

TABLE 1
TYPICAL ANALYSES OF NATURAL GAS

Specific Gravity (Air=1)	Dry gas: Pittsburgh	Oil well gas: Persia
	0.65	0.74
Analyses:	Per cent.	Per cent.
Methane	84.7	76
Ethane	9.4	12
Propane	3.0	6
Butanes and higher	1.3	3
Nitrogen	1.6	—
Hydrogen sulphide	traces	3

Among the constituents of natural gas the butanes and higher hydrocarbons are readily liquefiable. From these gases, so-called *natural gasoline* can be obtained by simple compression of the gas, by adsorption (as for example in active carbon), or by use of a solvent. Natural gasoline is very volatile and may be mixed with straight-run petrol derived from crude petroleum; it is characterised by good anti-knock properties. Furthermore, propane and butane can be stored in cylinders, and form an increasingly important readily portable type of gas of high calorific value (see "bottled gas", below).

PETROLEUM

There are three main classes of hydrocarbon constituents in crude petroleum:

Class	Generic Formula	Example
Paraffins	$\text{C}_n\text{H}_{2n+2}$	Butane, C_4H_{10}
Aromatics	—	Benzene, C_6H_6
Naphthenes	C_nH_{2n}	Cyclohexane, C_6H_{12}

In addition olefines (C_nH_{2n}) are present in cracked petroleum products (see "Cracking" below). Crude petroleum must, therefore, be considered essen-

tially as mixtures of these hydrocarbons, though there are also present compounds containing carbon and hydrogen in combination with sulphur, nitrogen or oxygen. There are even some compounds containing mineral elements, e.g. vanadium. Individual hydrocarbons (as for example *n*-pentane, *iso*-pentane, and *neo*-pentane) can be separated from the lower boiling fractions such as those used as motor fuels, but it is extremely difficult at present to separate individual hydrocarbons from the higher boiling fractions of crude petroleum.

Petroleum refineries separate crude petroleum by distillation into a series of products as follows:

Motor Spirit—petrols (gasolines) of various degrees of volatility, distilling within the range of about 30°C. to 200°C., with 30 per cent. to 60 per cent. distilling up to 100°C.;

Solvent spirits—white spirit (turpentine substitute or paint thinners) and industrial solvents of various distillation ranges, usually within the figures quoted for motor spirit;

Burning oils (so-called paraffin oil or kerosine) ranging from the familiar household illuminant to lighthouse and signal oils distilling within the range 150°C. to 300°C. Kerosine is also used as a fuel for aircraft turbine engines;

Vaporizing oils or tractor fuels, distilling from about 150° C. to 280° C. but with about 40 per cent. distilling up to 200° C.;

Gas oil, for the enrichment of water gas, and fuel for compression-ignition (i.e. diesel) engines and a variety of burning purposes.

Lubricating oils, from the lightest spindle oil to the most viscous steam cylinder oil;

Paraffin wax of a range of melting-points, used for candle manufacture, the proofing of paper and for match impregnation;

Bitumens for road surfacing and road aggregates, for general waterproofing purposes such as the impregnation of felts, as a paint and as an electrical insulator for cables;

Distillates and residual oils from heavier fractions, used as fuel oils for furnaces;

Petroleum Coke. If distillation is continued to the extreme limit, a solid residue of nearly pure carbon known as *petroleum coke* remains. This is used principally for the manufacture of electrodes for the electro-metallurgical industries.

THE DISTILLATION OF PETROLEUM

Distillation is the first step in the process of separating petroleum into the basic products gasoline, kerosine, gas oil or diesel fuel, fuel oil and bitumen. *Batch distillation* of crude petroleum in a kettle or still, followed by condensation of the vapours, was replaced by a *cascade process* in which the crude petroleum was passed continuously through a sequence of connected stills, heated to successively higher temperatures. This gave a series of fractions with a progressive rise in boiling-point.

Except for small scale operations, cylindrical stills have now been entirely replaced by pipe or tube stills (see Fig. 1). In these, the petroleum is pumped through a continuous pipe in a furnace and then passed into a flash tower or fractionating tower. The volatile components vaporize and the less volatile components remain as liquid. The overhead vapour, usually gasoline, is condensed and other distillate fuel oils are drawn off as side-streams from the fractionating tower.

The more volatile gasoline fractions were originally of little or no value, the main product wanted by the consumer being the kerosine or lamp oil. The demand for motor and aviation fuels developed particularly in the period

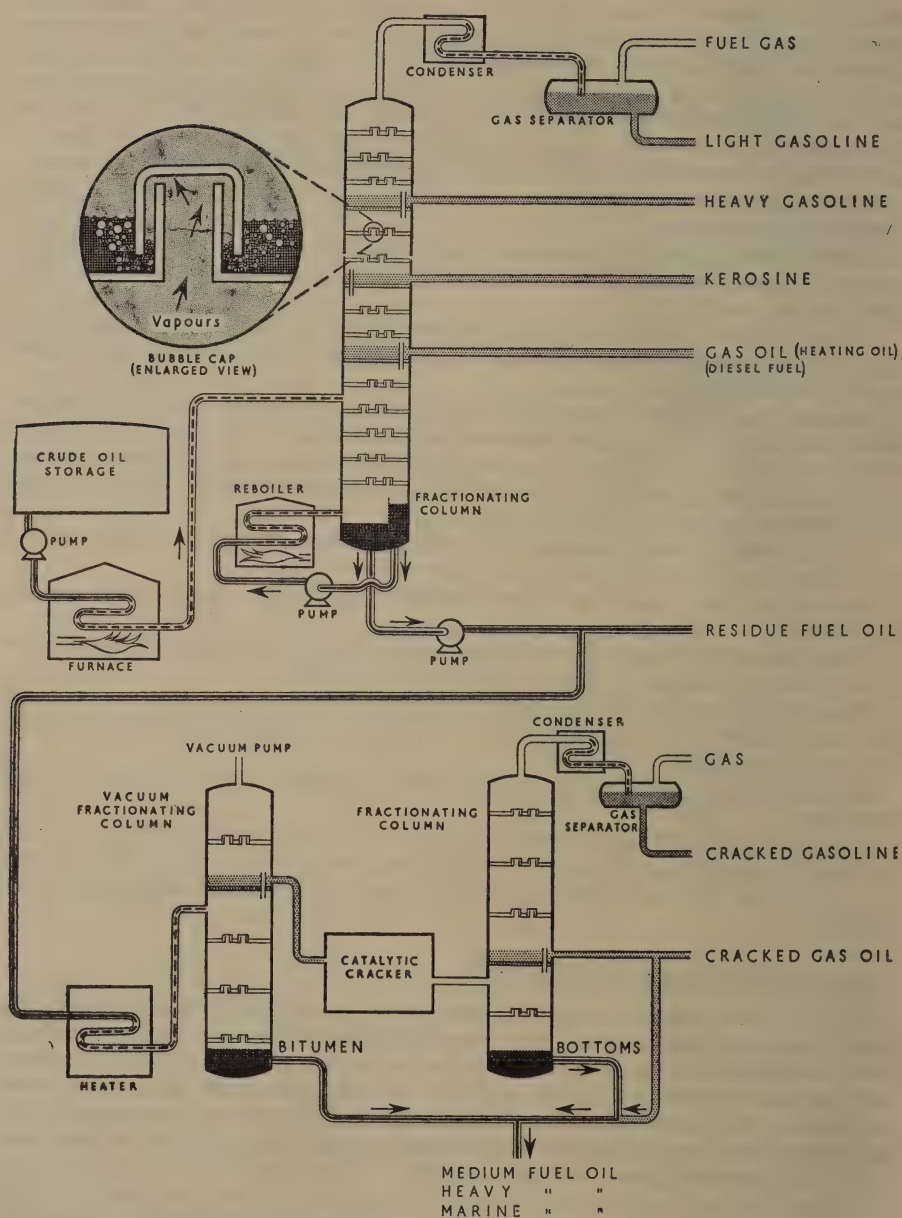


FIG. 1. Distillation and catalytic cracking of petroleum.

1914–1918, and more efficient fractionating devices were gradually developed so that a better separation could be effected between the main products. The bubble cap tower, originally developed in the alcohol distillation industry, replaced the earlier fractionating devices such as the packed column, or columns of the disc and doughnut type.

The proportions of the main products from crude petroleum seldom correspond with the market demand, particularly as regards petrol, of which 20–25

per cent. is present in many crude petroleum, whereas in some markets the demand may be in the neighbourhood of 45 per cent. In consequence, *cracking* processes were developed to convert higher boiling fractions such as gas oil into cracked gasoline for blending in the production of petrol.

Fig. 1 is a schematic and simplified diagram illustrating the main steps in the treatment of petroleum to produce fuels.

In a modern distillation plant of say 4,000,000 tons a year capacity, pipe stills and heat exchangers of various types are combined so as to obtain maximum heat economy and products requiring a minimum of subsequent refining to make them suitable for the market.

It is perhaps in the field of aviation fuels, with the demand for very high Octane Numbers (see below), that the process of distillation has seen its greatest development particularly for the segregation of hydrocarbon components such as *iso*-pentane (C_5H_{12}) of high octane number from crude petroleum; these can be incorporated in aviation fuels. Normal hexane (C_6H_{14}) and normal heptane (C_7H_{16}) which have *very low* octane numbers are first removed in order to raise the octane number.

Propane and the butanes are separated for marketing as liquefied fuel gas ("bottled gas") and as raw materials for the manufacture of chemicals and of other hydrocarbons used as components of aviation fuels.

Diesel fuels and fuel oils do not generally require chemical refining; some diesel fuels are treated to remove naphthenic acids, and processes are in use to lower the sulphur content.

THE CRACKING PROCESS

When heated to high temperatures, of the order of 800–1,000°F., hydrocarbon oils decompose, giving, at first, mainly lower boiling products. The process is known as *cracking* and is always associated with the formation of a heavy residue or coke and uncondensable gases. Before about 1940 simple thermal cracking was used to increase the yield of gasoline, but catalytic cracking, developed later, has largely replaced it.

In *thermal cracking*, which is brought about by the action of heat alone, gas oil or fuel oil is heated in a pipe still under pressures from 250 to 750 lb./sq. in. and then passed into a reactor or soaking drum. The vapours then pass through a reducing valve into a fractionating tower where the lighter products—mainly gases and motor fuel—are separated. The gas oil fraction and residue may then be re-circulated to the pipe still for further cracking. The residual product may be a fuel oil or petroleum coke.

In another form of thermal cracking, the higher fractions present in motor spirit are cracked, often without the use of a reactor, to give lower boiling-point fractions of higher octane number.

Viscosity breaking is a form of thermal cracking in which fuel oil is subjected to moderate temperatures and pressures to give a fuel oil of much lower viscosity than that of the original charging stock, and a low yield of light fractions.

A form of thermal cracking called *delayed coking* has been developed. This is primarily used to treat fuel oils in order to obtain gas oil distillates suitable for use as diesel fuel, as domestic heating oil or as a charging stock for catalytic cracking processes.

In *catalytic cracking*, petroleum vapours are cracked in the presence of solid catalysts, e.g., aluminium silicate, with or without the addition of special metals. In the original (Houdry) process, the vapours were cracked by passing them into a catalyst container; when the catalyst lost its activity owing to the formation of carbon, the vapours were diverted to a second vessel and the first

was steamed out. Later, as the activity in the second vessel declined, the vapours were passed to a third vessel and in the meantime the first vessel was "blown" with air, which oxidised the carbon, leaving the catalyst ready for further use in cracking. This process has now been largely displaced by continuous processes, of which the outstanding example is the *fluid catalytic cracking* process.

FLUIDIZED BED TECHNIQUE

Solid particles, when subjected to a current of air, may be:

- (a) unaffected if the air velocity is below a certain value
- or (b) airborne if the air velocity is above a certain higher value.

Between these two velocities a bed of small particles of fairly similar size will not become fully airborne, but will have their effective density reduced. Under these conditions the particles move about in the bed as if the bed were fluid and, by regulation of air velocities, the solid particles can be transferred about the plant almost as easily as if they were fluid. Any gas or vapour will have the same effect as air, due allowance being made for velocity and density. Thus, in the fluid catalytic cracking process, petroleum vapors are passed into a reactor chamber containing a finely divided solid catalyst which by the buoyant action of the rising vapour behaves as a fluid. Cracking takes place on the catalyst, forming carbon, and the used catalyst is continuously withdrawn into a regenerator vessel, where it is "blown" with air, the carbon on the catalyst being burned off and the catalyst fed back to the reactor chamber. The heat provided by the combustion is usually sufficient to operate the whole plant.

The catalytic cracking processes, which are carried out at very much lower pressures than in the thermal cracking process, give gasoline of higher Octane Number than that of gasoline produced by the simple thermal cracking process. Only negligible amounts of heavy residual products are formed in catalytic cracking, but the cracked gas oil formed is highly aromatic in composition and is mainly used as a component of furnace fuel oil.

From all cracking processes a large proportion of permanent gases containing olefines such as propylene and butylenes is inevitably produced; these serve as basic materials for the manufacture of high octane motor spirit by processes of polymerization, and alkylation, and also for the manufacture of so-called *petroleum chemicals* which is rapidly assuming the dimension of a major industry throughout the world.

SHALE OILS

Oil shale occurs in many different localities throughout the world. It contains no free oil but a material known as *kerogen* which, during the destructive distillation of the crushed shale in retorts rather like gas retorts, yields gas, crude shale oil and ammonia. The spent shale from the retorts has no fuel value but has been utilised for making bricks.

The crude shale oil is subsequently distilled by processes similar to those used for the treatment of petroleum.

In situ electrical heating methods (i.e., heating the shale underground) have been employed in Sweden for distilling the oil from the shale beds—thus avoiding the mining of crude shale and the disposal of the spent shale.

Table 2 indicates the approximate yields of oil from some typical shades.

TABLE 2
APPROXIMATE YIELD OF OIL FROM TYPICAL SHALES

<i>Origin</i>	<i>Yield of Oil: gal. per ton</i>
Torbanite (Scotland)*	124
Scottish shale	20
Estonian Kukersite	25-78
South African Torbanite	28-110
New South Wales	80-162
Colorado shales (Rifle)	13-25
Autun (France)	20

*Now worked out.

The estimated world reserves of oil shale are very large; those in the U.S.A. alone have been recently estimated as equivalent to 320,000 million barrels of oil. As petroleum reserves show signs of depletion, this source of oil may become increasingly important.

The crude oil from the retort is distilled by conventional petroleum distillation methods to give motor spirit, paraffin oil (kerosine), gas oil and paraffin wax. Sometimes there is a substantial residue, in coking stills, of paraffin coke—a very high grade almost ash-free smokeless fuel. The refining of the various oils follows normal petroleum practice. The motor spirit, consisting mainly of paraffinic hydrocarbons with smaller amounts of olefines, is of low Octane Number but its anti-knock quality can be improved (as in the case of motor spirit from petroleum) by adding tetra-ethyl lead. The diesel fuel is of high quality, as shown by its high Cetane Number. The kerosine and gas oil fractions can be used for the same purposes as the corresponding fractions of petroleum.

Most shale products in Britain are derived from the Lothians shales of Scotland. Some shale deposits occur at Kimmeridge in Dorset, but their very high sulphur content renders their products unsuitable for the market, though the increase in world need for sulphur might eventually make these deposits valuable as a source of sulphur.

Table 3 gives some of the properties of the main products manufactured at present from Scottish shale

TABLE 3
SCOTTISH SHALE FUELS—TYPICAL ANALYSES

<i>Criteria and properties</i>	<i>Motor spirit</i>	<i>Diesel oil</i>	<i>Shale oil coke</i>
Sp. gr. at 60°F.	0·72	0·84	—
Sulphur	0·10%	0·32%	0·5%
Octane Number	61	—	—
Cetane Number	—	54	—
Viscosity (Red. l. at 100° F.)	—	34 sec.	—
C.V.: B.t.u./lb. gross	20,150	19,530	14,800
Flash point	—	174° F.	—
Pour point	—	10° F.	—
Ash	—	—	0·6%

OILS AVAILABLE FOR FUEL PURPOSES

The principal characteristics of some oil fuels are given in Table 4; Fig. 1, Chapter 13, gives the approximate viscosity/temperature curves of four typical liquid fuels. Some of the properties of creosote: pitch mixture, known as CTF 200 are also given for convenience. The Coal Tar Fuels are further discussed in Chapters 3 and 13.

GAS OIL FOR GASWORKS

The gas produced by the cracking of gas oil is used to enrich water gas for increasing its calorific value, thereby producing a gas suitable for industrial and domestic use (see Chapter 3). In general, paraffinic hydrocarbons are preferable in an oil required for this purpose and the aromatic content should be as low as possible. Thus a good gas oil should have properties similar to those necessary in a fuel for a diesel engine. Analytical methods have been devised for determining in gas oils the percentages of unsaturated, aromatic, naphthenic and paraffin hydrocarbons, and the sum of the percentages of paraffin and unsaturated hydrocarbons has been described as the *Valuation Number*. The higher the Valuation Number the greater the number of gaseous therms obtainable per gallon of oil. Since gas oils are limited in supply, there has recently been a tendency to replace them for gasworks use by fuel oils, with the necessary modifications of the carburetting plant. In addition, catalytic processes have been developed to make gas from fuel oils instead of from the more costly gas oil.

FUEL OILS

In this Chapter the main emphasis is laid on fuel oils and the problems relating to their use in furnaces and boilers. Fuel oils include a variety of products, from distillates such as gas oil to residual oils, as well as blends of distillate and residual oils. These oils have a wide range of viscosity, but for practical purposes the viscosity must be such that they will flow readily from the storage tank to the burner and can be effectively atomised. Reduction in viscosity may be brought about by raising the temperature of the oil. The selection of a suitable grade of fuel oil is thus largely dependent on the equipment in which it is to be used and on the facilities available for heating the fuel in order to lower the viscosity. (See Chapter 13.)

The basic principles of combustion and furnace operation described elsewhere in this book are equally applicable to oil burning; particular attention is here given to the special aspects that relate to the burning of oil fuel.

CRITERIA FOR FUEL OILS

The following characteristics, determined by the laboratory tests prescribed by the Institute of Petroleum¹, are generally used for assessing the nature and quality of fuel oils.

SPECIFIC GRAVITY

This is the ratio of the weights of equal volumes of the oil and of water, both determined at 60° F. The measurement is generally made by hydrometer, a suitable correction (approximately 0.00037 per deg. F.) being added if the temperature of the oil is above 60° F., or subtracted if below 60° F. The specific gravity is no criterion of the *quality* of an oil; its main use is in calculations involving weights and volumes.

VISCOSITY

This is one of the most important criteria of fuel oils from a practical standpoint (see Chapter 13). For practical purposes, viscosity is measured in terms

TABLE 4
 TYPICAL PROPERTIES OF SOME OIL FUELS

<i>Criteria</i>	<i>Kerosine</i>	<i>Gas Oil Diesel Fuel</i>	<i>Fuel Oil</i>	<i>Heavy Fuel Oil</i>	<i>Marine Fuel Oil</i>	<i>Creosote, Pitch C.T.F. 200</i>
Nature	distillate	distillate	residual or blended fuels			
Viscosity, Redwood I .. secs. at 100° F.	—	34	200	900	3,000	1,000 to 1,500
“ centistokes at 100° F.	2.0	3.4	49	222	741	250 to 370
Flash Point (not below figure quoted) °F ..	100	150	150	150	150	150
Distillation Range: °C. (approx.)	150 to 300	200 to 360	—	—	—	—
Carbon Residue per cent.	Nil	below 0.05	about 6*	about 8*	about 10*	over 10%*
Pour Point °F.	—40	10	20	40	50	—
Sulphur, per cent. wt.	0.1	up to 1.0	up to 3.2	up to 4	up to 4	0.85
Ash, per cent. wt.	Nil	up to 0.01	up to 0.05	up to 0.12	up to 0.2	0.25
Cetane Number	—	45	—	—	—	—
Diesel Index	—	48	—	—	—	—
Specific gravity 15° C./4° C.	0.79	0.84	0.935	0.95	0.97	—
gal./ton	284	267	240	237	230	—
Calorific Value, gross, B.t.u./lb. (approx.) ..	20,000	19,600	18,800	18,600	18,300	16,500
“ “ net “ “ ..	18,700	18,400	17,700	17,600	17,400	15,600

* Not normally determined on fuel oils.

of the time (e.g., number of seconds) taken for a standard volume of oil to flow through a standard orifice at standard pressure and temperature. The influence of temperature on viscosity is very great, all oils becoming much less viscous—more “fluid”—as their temperatures rise.

The apparatus in general use in Britain for furnace oil fuels is the No. 1 Redwood Viscometer and the viscosity of an oil is expressed in “seconds” Redwood I at $t^{\circ}\text{F.}$, t being the temperature (100° or 122°) at which the test is made. As the Redwood Viscometer cannot be used for oils with a time of flow less than 30 seconds, the viscosities of very fluid oils, such as kerosine and certain gas oils and diesel fuels, are usually determined in a viscometer of the Ostwald type. The viscosities are then expressed in metric units (centistokes).

In America the standard instruments are the Saybolt Universal and Saybolt Furol Viscosimeters, Continental Europe favouring the Engler Viscometer. In order to avoid the difficulties of translating the results from one to another there is a growing tendency, particularly in specifications used internationally, to measure and express all viscosity values in centistokes.

Approximate relations between these units are as follows:

$$100 \text{ centistokes} = \begin{cases} 1 & \text{stoke} \\ 407 \text{ sec.} & \text{Redwood No. I} \\ 460 \text{ sec.} & \text{Saybolt Universal} \\ 46 \text{ sec.} & \text{Saybolt Furol} \\ 13.3 \text{ Deg.} & \text{Engler} \end{cases}$$

For more accurate conversion factors the authoritative Tables in “Standard Methods for Testing Petroleum and its Products”¹ should be used.

Absolute viscosity, the metric unit of which is the *poise*, is the product of the specific gravity and the kinematic viscosity in stokes. It is rarely used in petroleum technology except for calculations of pipeline throughput. (See Viscosity, Chapter 10).

CALORIFIC VALUE

Whereas the calorific value of coals varies considerably, depending on ash and moisture content, as well as on the coal type, calorific values of fuel oils are much more consistent. (See Chapter 30.)

FLASH POINT

This is the temperature at which an oil, when tested in a standard apparatus, gives off just sufficient vapour to create, in the air space above it, an explosive mixture that will “flash” if brought into contact with a flame. It is thus a measure of the fire risk of an oil in bulk. The permissible conditions of storage and use are different for products with flash points below 73°F. , between 73° and 150°F. (kerosine and vaporizing oil), and above 150°F. (gas oil and fuel oils), being less stringent as the flash point rises.

Oils with flash points below 73°F. including motor spirit (gasoline), which has a flash point well below 0°F. , i.e., 32°deg. F. below freezing, are regarded, for transport and storage purposes, as “Dangerous—highly inflammable,” and are subject in Britain to strict Home Office regulations. They must be labelled accordingly. Fuel oils, which normally flash above 150°F. , are regarded as “safe”.

In Britain two standardized forms of testing apparatus are used; the Abel Tester for fuels with flash points below 120°F. (e.g., kerosine and vaporizing oil, which flash at about 100°F.) and the Pensky-Martens Tester, for those oils with flash points above 120°F. (e.g., gas oil, diesel oil and fuel oils, which flash between 150°F. and 250°F.). The corresponding American instruments are (a) the Tag and (b) the Pensky-Martens. The Tag instrument gives readings about 5 deg. F. higher than the Abel.

It is important to avoid confusion between Flash Point and the entirely unrelated *Spontaneous Ignition Temperature* (S.I.T.). The latter is the temperature at which a combustible substance will ignite, i.e., burst into flame, in the presence of air, without any flame or spark being applied. The S.I.T.s of petroleum fuels vary very considerably according to the apparatus used and no generally accepted test method for their determination has so far been devised. Most petroleum oils have S.I.T.s between 500° F. and 700° F.

POUR POINT

This is the temperature 5 degrees Fahrenheit above that at which the oil ceases to flow when cooled and tested according to the prescribed method. It indicates the extent to which the oil resists congealing at low temperatures. This cessation of flow may be due solely to an increase in viscosity, or it may be caused by the build-up of a delicate structure of wax crystals within an oil that is otherwise still fluid. In the latter case, the fuel may be pumpable at temperatures well below its pour point, once the structure has been broken, but it will not *flow spontaneously* under a small head, especially in narrow-bore pipes. Fuel oils derived from crude oils of very low wax content have generally substantially lower flow points than those derived from wax-bearing crudes.

CLOUD POINT

This is the temperature at which, during the determination of pour point of distillate fuels, a haze of small wax crystals becomes visible in the sample under test. It is of importance only in respect of diesel oils that may have to pass through very fine filters, as the filters may become clogged by very small amounts of such solid matter.

SULPHUR CONTENT

All petroleum oils contain organic sulphur compounds, the quantity depending on the source of the crude oil. The amount is small in the case of kerosine, and is progressively greater in the heavier grades of fuel. Typical figures are as follows:

SULPHUR CONTENT OF OILS

	Per cent.
Kerosine	0.05—0.2
Vaporizing oil	0.1 —0.4
Gas oil, diesel oil	0.3 —1.5
Fuel oil	2.0 —4.0
Coal tar fuels	0.5 —1.0

High-sulphur fuels have certain disadvantages. With furnace fuels, the main disadvantage is risk of corrosion by sulphuric acid formed during and after combustion and condensing in cool parts of the stack or flues; with diesel fuel there is some evidence that sulphur increases cylinder wear and "lacquering", creating the necessity for a detergent lubricating oil; in the case of kerosine, the main disadvantage lies in the odour of the combustion products, mainly that of the sulphur dioxide. If a very large amount of sulphurous fuel oil is burned, for example at a power station, special steps may be necessary to avoid creating a public nuisance on account of the sulphur dioxide discharged into the local atmosphere. These may range from increasing the height of the stack to the costly remedy of washing the stack gases.

In certain metallurgical and other industries, where sulphur may be extremely detrimental (as, for example in oil-fired open-hearth, melting and re-heating furnaces), it is customary to use selected fuels with the minimum sulphur content.

DISTILLATION TEST

The purpose of this test is to ascertain the range of temperatures over which the oil boils. Using prescribed standard apparatus, it is carried out by distilling a measured quantity of the oil from a flask provided with a thermometer and a condenser, and recording the exact temperature when each successive 10 per cent. of the liquid has distilled (see Chapter 30). The test gives useful information regarding distillate fuels such as motor spirit, kerosine and gas oil (diesel oil), but is not generally applied to residual fuel oils (furnace oils) which cannot be distilled without cracking. The approximate boiling range of kerosines is 150° C. to 300° C. and of distillate diesel fuels 200° C. to 360° C.

CARBON RESIDUE

This test gives an indication of the tendency of an oil to deposit a carbonaceous solid residue on a hot surface, such as a burner or injection nozzle, when its vaporisable constituents evaporate. A weighed quantity of the oil in a covered crucible or a glass bulb is slowly heated to redness in the absence of air until all volatile matter has disappeared; the residue of coke is weighed. There are two variations of the test method, the Conradson, and the Ramsbottom; the latter is to be preferred. Distillate oils give very low carbon residue (less than 0.1 per cent.); residual oils give results ranging from 1 per cent. to 10 per cent. or more. The two methods do not necessarily give the same result.

ASH

The inherent ash content of distillate fuels is *nil*. Any incombustible material present consists of adventitious impurities such as iron rust and dust.

Residual fuel oils generally contain, in addition to traces of iron rust derived from tanks, pipe lines, etc., small quantities of insoluble mineral matter and salt. Traces of nickel and vanadium occur in solution or in combination with certain oils: flue deposits from the burning of Venezuelan fuel oil can actually constitute a commercial source of vanadium. The ash content of fuel oils rarely exceeds 0.25 per cent.

Certain problems that may arise on account of the presence of vanadium in some petroleum fuels are referred to at the end of Chapter 13.

FUELS FOR INTERNAL COMBUSTION ENGINES

OCTANE NUMBER

The compression ratio of internal combustion engines of the spark ignition type is limited in practice by the tendency of the hydrocarbon fuels to detonate (knock). This tendency is measured by determining "knock ratings" of the fuels in a standard engine in terms of the relative performance of two standard fuels. The *Octane Number* of a petrol (gasoline) is numerically equal to the percentage by volume of *iso*-octane in a mixture of *n*-heptane and *iso*-octane having the same knocking tendency as the fuel being tested. This mixture is selected because *n*-heptane has had anti-knock properties and *iso*-octane has extremely good anti-knock properties.

CETANE NUMBER

This is an important criterion for diesel fuels, particularly those used in the relatively small high-speed engines of road vehicles. A high Cetane Number implies ease of starting from cold and a minimum of the "ignition delay" that is the cause of "diesel knock".

The Cetane Number of a diesel fuel is defined as the percentage of cetane in a mixture of cetane with alpha-methyl-naphthalene showing the same ignition quality as the fuel being tested, when tested in a diesel engine. It is, therefore, a *figure of merit* that must lie somewhere between that of pure cetane (rated as 100) and pure alpha-methyl naphthalene (rated as 0).

A good quality fuel for diesel-engined road vehicles shows a Cetane Number of 45 or over. Lower grades of diesel fuels (which may still be quite satisfactory for slow-speed engines) may have Cetane Numbers between 30 and 40; those with Cetane Numbers below 30 are suitable only for very large slow-speed diesel engines used in motor vessels or power stations. In general, paraffin hydrocarbons have the highest Cetane Numbers and aromatic hydrocarbons the lowest, with naphthenes occupying an intermediate position.

DIESEL INDEX

This is an empirical figure which—like the Cetane Number—indicates the ignition quality of a diesel fuel. It is usually employed when there are no facilities for directly determining the Cetane Number. It is calculated from a formula based on the Aniline Point and the gravity (on the American Petroleum Institute Scale—see Chapter 30) and is usually between 0 and 5 units higher than the Cetane Number of the fuel.

For a comparative study of the terminology of oil fuels in Britain and in other countries the reader is referred to the paper by Martin on The Characteristics of Oil Fuels².

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CHAPTER 5

STORAGE OF COAL

THE chief object of storing coal is to provide reserves so that power plants and factories may be kept working when supplies are irregular or interrupted. Disturbances in the even flow of supplies may be due to a shortage of coal at the source, or to a delay or diversion of transport, caused for example by the weather. An incidental advantage of storing coals is the possibility that a stock of coal built up on a single occasion may assure a more uniform fuel for a longer period than if regular deliveries are relied on for maintaining the supply to the plant.

Laying in a store of coal may also benefit industries other than the consumer's; building up a coal stock in the summer to meet increase in consumption during the winter helps to reduce the seasonal fluctuations in the demands on the mining and transport industries.

Stored coal, however, is subject to deterioration and may get hot and ignite spontaneously. It is important to avoid or minimize these effects.

THE OXIDATION OF EXPOSED COAL

It is well known that a coal stock may, by self-ignition, render its untimely consumption necessary unless it is to be lost by being burnt completely. It is perhaps not so widely appreciated that as soon as the atmosphere gains access to the coal in mining operations two processes are initiated: the first, a chemical change, is the oxidation process accompanied by the liberation of heat; the second, of a physical nature, is disintegration or degradation in size.

Oxidation adversely affects the useful properties of the coal; the caking power, for example, is impaired. As this oxidation, considered from a strictly scientific point of view, is the very first stage in a process of combustion, some heat is evolved, so less is available when the coal comes to be used.

The mechanism of the oxidation process is neither simple nor perfectly understood. Well recognized steps in the process include:

1. the physical absorption of oxygen by the coal, occurring at any temperature up to, perhaps, 200°C.:
2. the slow interaction of the coal and the absorbed oxygen to produce a "coal-oxygen complex" and some gaseous products—in fact, combustion products—oxides of carbon and water vapour;
3. at higher temperatures, above 200°C., a more rapid evolution of the gaseous products of combustion, so that the stage of the "coal-oxygen complex" may seem to be by-passed.

The second process goes on very slowly at ordinary temperatures but increases in rapidity as the temperature is raised.

Figure 1 shows how the amounts of oxygen absorbed and of oxides of carbon evolved may vary with the passage of time at temperatures at which they are readily measurable.

THE HEATING OF STORED COAL

The heat generated by the oxidation of coal exposed to the air may be so slight, or may be dissipated so rapidly, as to be imperceptible. But under suitable conditions the coal may become noticeably warm and then so hot that it is thermally decomposed or actually ignited.

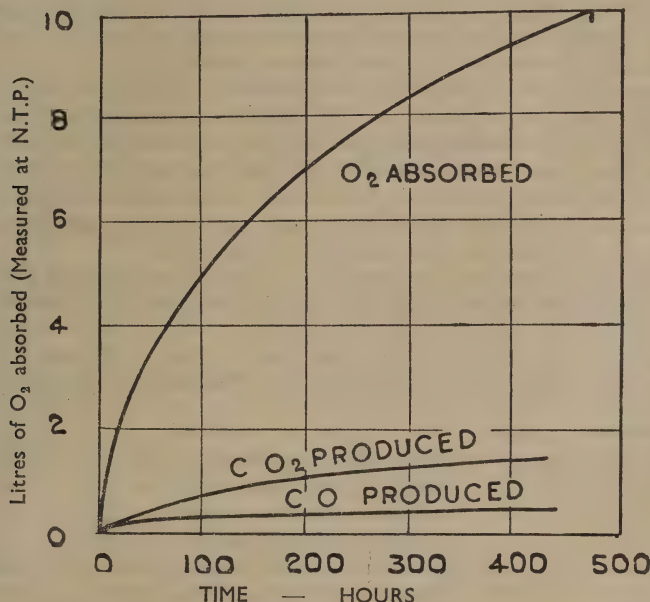


FIG. 1. Rate of absorption of oxygen by a coal.

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Whether the heat caused by this oxidation can or cannot accumulate sufficiently to become perceptible depends on a combination of circumstances. There are three conditions all of which must always apply before coal begins to get hot in storage. These are:

- (a) the quantity of coal must be large;
- (b) the coal must be of a susceptible type;
- (c) much of the coal must be fine, less than $\frac{1}{16}$ inch in size.

Of these three factors, the first, the quantity of coal, is of unique significance. In a small bulk of coal, the heat of spontaneous oxidation is dispersed so rapidly as not to become perceptible. No attempt to detect spontaneous heating on a laboratory scale has ever been successful. The condition that heat shall not be dissipated so easily that it can accumulate and manifest itself, makes spontaneous combustion an exclusively large-scale phenomenon.

As to the other two conditions, some coals are relatively so unreactive as not to show any spontaneous tendency to heat at all; and only fine coal offers enough surface relative to the bulk of the coal for the absorption of oxygen to occur extensively enough to raise the temperature of the coal appreciably.

THE EXTENT AND COURSE OF SPONTANEOUS HEATING

Oxidation giving rise to noticeable heating is subject to three influences. The first is that a rise in temperature causes an increase in the rate of oxidation. A rise of 10 deg. C. (18 deg. F.), for example, causes the speed of a chemical reaction proceeding at about atmospheric temperatures to be approximately doubled. This increase in the rate of oxidation, in turn, aggravates the rise in temperature, so that the process is self-accelerating. Secondly as the temperature rises the rate at which heat is dissipated increases. Thirdly, as oxidation progresses, the reactivity of the coal towards oxygen diminishes

and so the rate of oxidation decreases. The latter two influences oppose the first one. According as a balance is struck for a time between these opposing influences a more or less steady condition may result.

Sometimes a balance may be achieved between the rate of heating and the rate at which heat is dissipated, but if the rate of heating is dominant, the coal eventually gets hot enough to ignite. On the other hand, if, after a certain temperature rise, the second influence, the rate at which heat is dissipated, becomes relatively more effective, the rise in temperature will cease at some point below that at which ignition occurs, and the coal settles down at a temperature that is more or less steady for some time.

If this stage is reached, the third influence, the diminution in the reactivity of the coal, gradually asserts itself, so that a mass of coal that has heated only to a moderate degree slowly cools thereafter.

The course of events as a store of coal heats up to a temperature at which spontaneous combustion becomes inevitable is somewhat as follows:

<i>Temperature</i>	<i>Result</i>
Any above atmospheric:	water vapour is evolved and may be visible as a mist in cool humid weather.
Up to 50–80° C.:	slow absorption of oxygen.
Above 50° C.:	oxidation accelerating.
About 80° C.:	a period at a steady temperature (probably while the coal is drying out).
100 to 120° C.:	evolution of oxides of carbon begins.
100 to 180° C.:	interaction of oxygen and coal accelerating rapidly.
180 to 250° C.:	thermal decomposition begins; beginning of evolution of tarry vapours, detectable by their odour and as a bluish smoke.
250 to 350° C.:	the hottest zones within the coal mass move against air flow, appearing as fires at the surface of the coal.

THE PRACTICAL PRINCIPLES OF COAL STORAGE

Some of the practical principles to be observed in safely storing coal can be deduced from what has already been said, and these principles may be summarized as follows:

	<i>Conditions favourable to safe storage</i>	<i>Conditions unfavourable to safe storage</i>
Size of coal	.. Nuts, cobbles, round coal; exclusion of fine coal	Fines; smalls; run-of-mine, alone or included with large coal; smalls formed by breakage, such as by falling from a chute.
Size of store	.. Less than about 200 tons.	More than 200 tons.
Height of store	.. Not greater than 6 to 8 feet.	Greater than 8 feet.
Ventilation	.. Adequately promoted; or what is generally easier, effectively suppressed.	Moderate or natural, especially if due to passages caused by segregation during stacking, owing to a zone of larger coal through the heap or against pillars or walls.
Age of coal	.. Greater than 3 to 6 months after mining.	Less than 10 weeks after mining.
State of coal	.. Having heated and cooled.	Freshly wrought.
Type of coal	.. Hard or dull, anthracite, anthracitic coal, splint, cannel.	Soft and bright; bituminous, sub-bituminous, lignitic.
Site of stack	.. Most open situations on clean, firm ground.	Near a source of heat, such as a boiler-house wall, or overlying steam pipes, or mixed with organic waste or oily material.

Although it is advocated that ventilation should be suppressed, in a small heap or in one not too high, the ventilation that does occur and the distribution of air currents may help to keep conditions safe; consequently, with the smallest heaps the suppression of ventilation will not be so urgent.

The liability to oxidation is lessened with coal that has been exposed for some time, because some of the unstable constituents become oxidized. Old coal will not therefore be as susceptible as freshly-mined coal.

THE SIZE OF THE COAL AND THE CORRECT METHOD OF STACKING

Small coal is the cause of nearly all storage difficulties. In coals of mixed sizes, segregation contributes more than anything else to the cause of spontaneous heating, because the larger pieces of coal open the texture of the heap and facilitate the type of ventilation necessary for heating to proceed. By "coals of mixed sizes" are understood coals that include fines, and some run-of-mine coals. *Uniformly* fine coal is less likely to heat than mixed sizes. Where a heap including large or graded coal has an open texture, the movement of air through it will be enough to carry away any heat generated; where fine coal lies close and compact, the movement of air will be insufficient to cause much heat to be generated. Between these two, there will be some critical rate of air flow that will favour cumulative heating.

Singles (about one inch) and larger sizes are quite safe, provided that fines are not the result of handling. The danger of heating is greater under a chute where the finest coal falls or is formed by breakage. Sized coal should not, therefore, be dropped from a height when it is being stacked.

THE SUPPRESSION OF VENTILATION

Ventilation, especially in a large heap of coal, can be suppressed effectively more easily than it can be promoted. This is because attempts to ventilate large heaps often do not go far enough, although ventilation by the insertion of perforated pipes is sometimes practised with success. However, it is not practicable and generally not economic to ventilate any but the smallest heaps of coal effectively; and many ventilation pipes may make the picking up of coal a tiresome process. The fact that spontaneous combustion does not occur in small heaps of coal is a special instance of effective ventilation.

Ventilation can be reduced by avoiding segregation and by packing the coal tightly and uniformly, especially at the edges and on the sloping sides. Coal can be compacted by rolling it or running a bulldozer over it; this method seems to be finding greater use, and some concerns have even bought equipment primarily for this purpose. Blanketing with fine coal helps to suppress ventilation, especially if the fine coal is afterwards rolled; but it is not an absolutely reliable expedient. A dragline scraper may also contribute towards the consolidation of a coal handled by it; on the other hand, it leaves the edges of the heaps ragged. If the coal can be kept wet, ventilation is reduced still further because moisture decreases or even fills the spaces between particles, impeding the movement of air.

The stack may be surrounded by a wall to reduce ventilation. A permanent coal storage site may have a low wall most of the way round it to protect the base whence ventilating currents start.

Wind assists ventilation, and to reduce its effect the stack is best built elongated with its longer sides in the same direction as that of the prevailing wind; in Britain this frequently means south-west to north-east.

A method that is completely effective is to store coal under water, for example in a bunker that can be flooded, but such facilities are rare.

It has been found that ventilation can be adequately reduced by rolling the surface of a dump of coal and spraying it with road-tar in the same way as a summer dressing is applied to a road. Ventilation has been so effectively reduced by this means that a hot dump of coal has been induced to cool; and even if fires have appeared, they can be prevented from re-appearing and can eventually be suppressed by this method of dressing the dump with road tar provided that the exact spot where the fire is active is quenched with water immediately before the dressing is applied. The cost of this treatment can be economic if it is carefully planned and carried out.

THE DIMENSIONS OF THE STACK

Trouble seems rarely, if ever, to arise in heaps of less than 200 tons. It is usually easier to control the height of the stack than to limit the weight of coal in it. The really safe height of a heap of coal is probably less than five, or even four, feet. But this is too low for economic use of the stocking ground, and a compromise between this and an absolutely safe height may be put at eight feet. If the coal is of a suitable size it may be stacked up to 16 feet. Hard nuts can be stored safely up to 20 feet and larger coals and anthracite up to 30 feet.

A stack may be built up in stages, whereby the lower layers have had an opportunity to pass through their critical stages before the upper layers are added. Thus, a 6-foot stack may be increased to 10 feet after six months, or an 8-foot stack may be built up to 16 feet after nine months. But it is better, if a store of coal is built up in this way, to add thin layers at intervals; thus, 3 feet at first and a further 18 inches every three months. The advisability of adding to the heap may be judged by the temperatures in the lower parts. No coal should be added unless that in position is quite cool. The height of the stack should follow the contour of the ground, so that the coal in hollows is not deeper than is advisable.

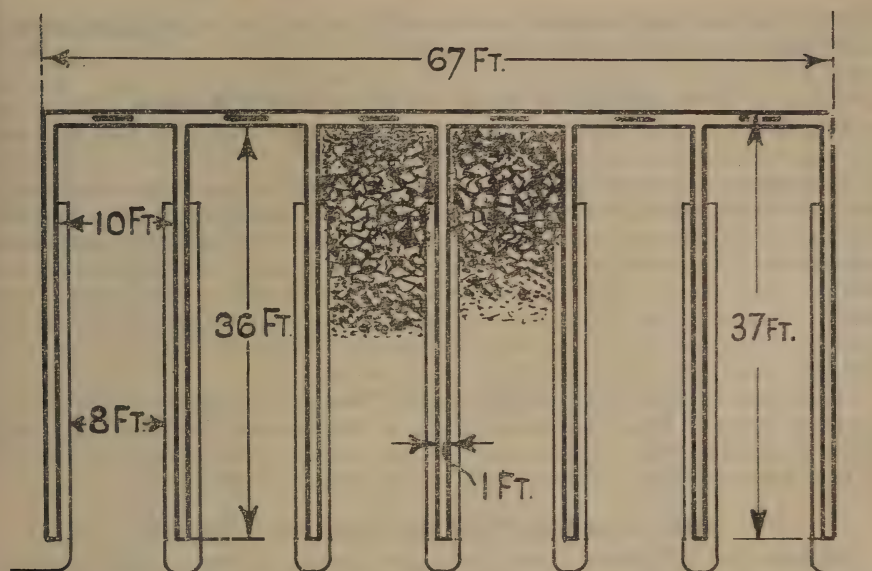
Coal in heaps occupies from 45 to 55 cubic feet per ton; the more mixed sizes give the more compact heaps, and the heap is also more compact when the heap is built up so as to avoid the segregation of sizes.

THE SITE OF THE STACK

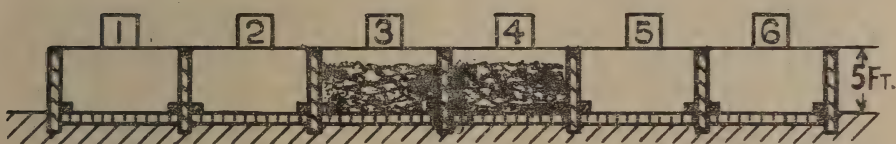
At the storage site, a most important consideration is to ensure the clean and complete recovery of the coal when it is required for use—the avoidance of “carpet loss”. A concrete floor provides an ideal base for a stack, but a well rolled floor of ashes may be satisfactory; hard clay or chalk may also be satisfactory. Peaty ground should be dressed with a few inches of ballast or ashes and then rolled to make it as firm as possible.

A convenient and tidy arrangement for small stores of coal serving day-to-day consumption, especially if the coal is delivered in lorries, is in the form of storage bays made by dividing a concrete-floored area 30 or 40 feet wide into 10-foot strips by 5-foot brick walls and joining these at one end by a similar back wall along one side of the area (Fig. 2). This gives a bay into which a lorry can back; half a dozen such bays, covering an area 70 feet by 30 or 40 will hold some 300 tons of coal divided into small lots of a safe height. In order that backing lorries and the ends of the partition walls may not damage each other, it is advisable to build a kerb around the end of each wall at the entry of the bay¹.

If a special floor cannot be prepared on a storage site, the surface should be cleared; and rank vegetation and waste organic matter should be removed, because these can contribute to the start of heating.



PLAN



SECTIONAL ELEVATION

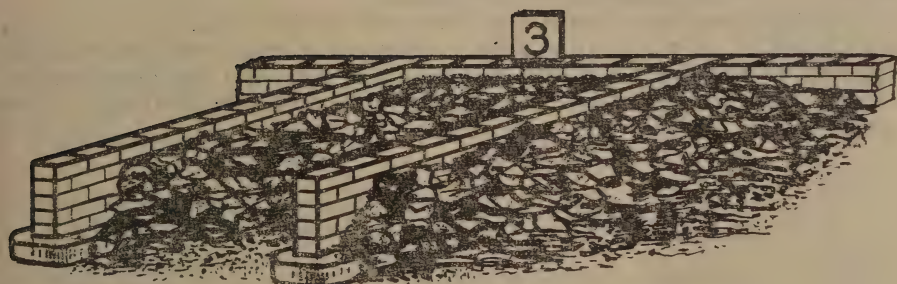


FIG. 2. Layout and construction of coal storage bays.

A wet site is not recommended. Storage under cover specially constructed offers no advantage to compensate for the outlay in providing the cover. The site of a coal store, and the coal on it, should always be disposed so

that all parts of the coal stock are accessible to such travelling appliances as travelling cranes-and-grabs and to lorries.

THE PERIOD OF ACTIVITY IN A HEAP OF COAL

Coal oxidizes most rapidly when it is freshly mined, and the rate at which it is affected decreases as time passes.

Spontaneous combustion usually occurs within four weeks to four months from the time when the coal has been laid down; but if the coal has arrived at the stocking ground already warm from a previous period of storage—a contingency that must always be watched for—it may fire in less than four weeks. A coal that is eight months old can be regarded as safe if there is no heating in the heap or if what heating there is is not worsening; but a coal that has been well sealed has been preserved in a more or less fresh condition and may heat when it is disturbed, whatever its age.

It is widely believed that putting freshly wrought coal down on old coal is a common cause of fires. This is not a source of trouble in itself; but obviously if the old coal is warm, or if a zone of open texture is left where the two lots of coal are contiguous, a dangerous condition may develop.

THE DETERIORATION OF COAL ON STORAGE

Deterioration obviously depends on the amount of heating that has gone on in a store of coal; if there is no appreciable heating, deterioration is slight. Although there are no data to indicate the depreciation of the various qualities of coal with time, it is possible and useful to know the order of the amount of deterioration to be expected.

Bright coals are affected more than dull, hard coals. A freshly broken surface is the most active for reaction with oxygen; and the surface of old coal loses its lustre in the course of time. This is said to affect the market value of the coal, but does not by itself indicate any appreciable depreciation in quality.

Loss of Caking Power. Of all the properties of a coal, the caking power is the most rapidly and extensively affected. Frequently the effect is most noticeable when there is no other indication of a change.

The caking power falls off much more rapidly during the first few months of storage than later. It is not known whether a coal ever loses all its caking power when it is stored, but coals that are originally poorly caking may lose practically all their caking properties. The rate at which caking power is reduced is also seriously affected by heating.

If caking power is an important characteristic of the coal to be stored, a coal should be selected with a higher caking power than would otherwise be required, so that it has a reserve of caking power to meet this deterioration.

Table 1 records the loss of caking power suffered by some Nottinghamshire coals.

TABLE 1
LOSS IN CAKING POWER OF STORED COAL*

Size of coal	Years in store	Caking power (Gray-Campredon)	
		Fresh	Stored
Large.. ..	5	21	6
Smalls	2½	16	6-7
Smalls	1½	9	2
Singles	1¼	7	3-4
Smalls	1	8	2-3

* From figures collected by the Fuel Research Station.

Loss in Calorific Value. Steam-raising power is often diminished by exposure to the weather and atmosphere, and is not unnaturally ascribed to a loss in calorific value. If the coal has not heated appreciably the loss in calorific value is slight, so slight as a rule as to be imperceptible. The loss in steam-raising power is likely to be due rather to an increased loss of small coal as unburnt matter falling through the grate.

If stored coal does not heat appreciably, the loss in calorific value rarely exceeds 0.5 to 1 per cent. per annum. Table 2, based on some carefully controlled experiments on a Forest of Dean gas coal², shows how the loss in calorific value is negligible with large coal, increases, though not seriously, as the coal is

TABLE 2
LOSS IN CALORIFIC VALUE OF STORED COAL

Size of coal	Loss in calorific value—Per cent.	
	After 1 year	After 2 years
Doubles	0.11	0.24
$\frac{1}{2}$ in.— $\frac{1}{8}$ in.	0.5	1.0
$\frac{1}{8}$ in.— $\frac{1}{16}$ in.	1.0	1.4
$\frac{1}{16}$ in.— $\frac{1}{60}$ in.	1.2	1.8
$\frac{1}{60}$ in.— $\frac{1}{80}$ in.	0.8	1.7
$\frac{1}{80}$ in.— $\frac{1}{120}$ in.	1.0	2.1
$\frac{1}{120}$ in.— $\frac{1}{180}$ in.	1.2	2.5
$\frac{1}{180}$ in.— $\frac{1}{400}$ in.	1.6	2.8
$\frac{1}{400}$ in.—0 in.	1.8	3.0

finer, and increases with time. An examination of 20 Scottish gas coals³ showed a mean loss of calorific value of 0.7 per cent. in three and a half to four years.

Similarly, experiments with a variety of Midland and Northern coals from nuts to smalls⁴ showed in four to five years a loss in calorific value of about 0.6 per cent., an average of 0.15 per cent. per annum for ventilated heaps.

If the coal heats, the loss in calorific value may become serious, according to the extent of heating.

Table 3 shows how the loss of calorific value, not very great at first, can increase with time, and can become very great when heating occurs.

TABLE 3
LOSS IN CALORIFIC VALUE OF STORED COAL*

	Time in store	Loss
	Years	Per cent.
<i>With no spontaneous heating:</i>		
†Loco. coals, mean of 11 varieties	1	0.45 (0–1.7)
†Nottinghamshire, mean of 5 varieties	2	0.85 (0–2.1)
	1.2	0.5–0.6
†Yorkshire loco. coal	1.1	1.8
	3.1	2.3
	7.4	1.9
†Derbyshire loco. coal	1.1	1.8
	3.1	2.4
	7.4	4.2
Scottish washed peas	several	2
Durham coking, run-of-mine	2	2–3
Northumberland washed smalls	6	2–3
Mixed nutty smalls	2½	2½–4
Durham and Northumberland smalls	several	4
Derbyshire nuts	6 8	5–7½
<i>With spontaneous combustion:</i>	months	
Various smalls and washed smalls	3–4	5–7½
Northumberland washed smalls	1½–2	10

*From figures collected by the Fuel Research Station. †Results of *ad hoc* experiments.

Gas Yield. A gas-making coal that has been stored shows a fall in the yield of gaseous therms when it is carbonized. This is of the order of two to four per cent. during periods up to four or five years.

Effect of Weathering on the Size of Stored Coal. Coal may disintegrate under the action of the weather, and small or fine coal is thus formed. This will not greatly affect the tendency of the coal to heat, for the coal is always likely to oxidize faster than it disintegrates.

Examples of the extent of disintegration are afforded by work done on Scottish coals³ and by the Fuel Research Station. Fourteen Scottish gas coals from which all coal passing a $1\frac{1}{2}$ -inch screen was removed contained from 3 to 20 per cent. of coal passing a $1\frac{1}{2}$ -inch screen after two years of exposure, and from 4 to 28 per cent. after 44 months. Six similar coals had originally from 30 to 45 per cent. of coal passing a 1-inch screen and this size was increased by up to 12 per cent. Table 4 summarizes the results of storing different types of coal in 2-ton heaps for periods up to one year.

TABLE 4
DISINTEGRATION OF STORED COAL*

Type of Coal	Period of storage—Months			
	0	6	9	12
S. Wales steam, $2\frac{1}{2}$ – $1\frac{3}{8}$ in. per cent.	100	93.2	91.6	90.7
Warwickshire house, $2\frac{1}{2}$ – $1\frac{3}{8}$ in. per cent.	100	91.4	90.0	87.3
Nottinghamshire house and steam, $2\frac{1}{2}$ – $1\frac{3}{8}$ in. per cent.	100	82.2	73.1	69.4
S. Yorkshire gas R, above 2 in. per cent.	43.7	37.4	34.7	30.8
S. Yorkshire gas, T, above 2 in. per cent.	54.0	46.3	48.2	47.8

*From experiments on stored coal at the Fuel Research Station.

Coal does not seem to break down progressively to the smallest sizes. The process appears to cease eventually when natural grades have been produced² owing to the splitting of the coal along bedding planes and at partings.⁵

Friability of Weathered Coal. The Warwickshire and Nottinghamshire coals used in the investigations at the Fuel Research Station^{5,6} were subjected to a test in a rotating drum in which the coal was dropped a few inches a few times in each revolution. Some of the results of these tests are reproduced in Table 5. These results show that a coal will break more easily when it is handled after weathering. This is important in boiler firing and other furnace work.

With small coal disintegration does not matter, but with large sized coal it

TABLE 5
FRIABILITY OF STORED COAL

Period of storage—Months		0	6	9	12
Warwickshire house	$2\frac{1}{8}$ – $1\frac{3}{8}$ in. per cent.	87.7	75.9	74.6	68.1
	$1\frac{3}{8}$ – $\frac{7}{8}$ in. per cent.	6.9	13.3	14.8	16.7
	under $\frac{7}{8}$ in. per cent.	5.4	10.8	10.6	15.2
Nottinghamshire house and steam	$2\frac{1}{8}$ – $1\frac{3}{8}$ in. per cent.	81.4	58.0	49.1	49.7
	$1\frac{3}{8}$ – $1\frac{1}{8}$ in. per cent.	9.6	15.1	16.8	17.1
	$1\frac{1}{8}$ – $\frac{7}{8}$ in. per cent.	4.7	12.1	14.4	13.7
	under $\frac{7}{8}$ in. per cent.	4.3	14.8	19.7	19.5

may be important. The size may be an essential quality of the coal, and in furnace work for example it may mean that there will be an undue loss of combustible material through the grate, and this, as previously indicated, will produce the impression that there has been a decrease in the calorific value.

Cannels and anthracites disintegrate little if at all, and dull, hard coals disintegrate less than soft, bright ones.

As most of the deterioration of a coal occurs in the *earlier* months of storage and as its rate is always decreasing—provided heating does not eventually accelerate it—stored coal should not be used while fresh supplies are available. In this way the loss is least because successive lots of fresh coal are not being exposed continually, and the rate at which the stored coal deteriorates is always falling; moreover, repeated handling is reduced and disintegration as well as labour costs are also lessened.

PRECAUTIONS TO BE TAKEN IN A STORE OF COAL

At regular intervals of about a week during the first three months of storage, the temperatures at different places in the stack should be observed.

A convenient method of doing this is to use $\frac{1}{2}$ in. or $\frac{5}{8}$ in. iron rods; they can be thrust into a heap of coal to any reasonable depth without serious difficulty, and can be pulled out and pushed back with ease. They are thrust vertically into the heap at intervals of 10 or 20 feet, with their ends projecting 3 or 4 feet. At intervals of a few days the rods are pulled up and felt to see how hot they are; if they are too hot to hold, the conditions are dangerous. Another indication is the rate at which the rods dry when they are pulled up, for they are usually wet in the heap.

It is more precise, though more troublesome, to use wrought-iron or steel pipes closed at their lower ends and to measure temperatures by lowering down them a thermometer with a cork on the bulb or a maximum-reading thermometer. The pipes should be built into the stack as it is made up. They should be from 15 feet to 50 feet apart, according to the size of the stack, the kind of coal and economic considerations. The temperatures at various depths can then be read; they should be recorded on a chart.

The temperature above which risk of spontaneous combustion must be expected varies considerably according to conditions and may be generally taken as about 70° C. (160° F.), but it may be lower if conditions are unfavourable.

A slow and steady rise in temperature must be expected; critical conditions are reached, and are followed by an accelerated temperature rise culminating in a fire. Adequate graphing or logging of the temperature-history of the respective points in the stack will give clear warning of this.

DEALING WITH FIRE IN A COAL STACK

When the critical temperature is reached, it is wrong to delay in the hope of a spontaneous improvement in conditions. If the precautions are not taken forthwith, a fire is inevitable, and the affected area will spread.

The danger usually occurs at points from 3 to 7 feet below the surface and fairly near the outer edges, where ventilation is sufficient to promote heating but the depth of coal sufficient to prevent a rapid enough loss of heat. Temperature observations will indicate the exact zone, which may also be shown by a light grey smoke and a distinctive odour.

Apart from the method of sealing by dressing with road tar, the only effective method for dealing with a fire is to take up the coal and use it. If the heated coal is dug up and scattered thinly so that it cools, the trouble *may* be alleviated, but this removal of coal lays open fresh sides of the heap, and if

the adjacent coal is warm, or if the heated coal is not completely removed, the fresh access of air may only lead to a spread of the trouble.

A crane-and-grab or similar mechanical appliance greatly simplifies this operation. If a fire has started, spraying with water is ineffective because in percolating through the coal it follows relatively narrow selected channels and so does not come into contact with the mass of the coal; and because it induces air currents.

In the early history of a stack of coal, however, spraying with water has a twofold advantage. It interferes with ventilation and may keep the temperature below its critical level while the heap is "nursed" through its peak heating period.

THE STORAGE OF OPENCAST COAL

During the 1939-45 War, coal supplies were supplemented by the opencast working of coal seams near their outcrops; this source of coal is still important. Under favourable conditions a seam, as it dips from its outcrop edge, is worked with suitable types of excavating machinery. The output of a productive seam becomes large at an early stage in the development of operations, and the storage of some or all of the coal close to the working or at selected storage sites is often necessary.

Generally, the outcrop edge of the seam is very inferior and has to be discarded. This is because it has become oxidized through long exposure to the air at the surface. Following the dip of the seam, the coal may still be rather poor, but it nearly always improves rapidly, at times approaching pit-coal in quality. It is usually more or less weathered and therefore generally has a high oxygen content with correspondingly diminished carbon and hydrogen contents and calorific value. It may also have a high inherent moisture content and be very friable. On the other hand, it is not uncommon for opencast coal to have a lower ash content than the coal from the same seam from a nearby pit; and some opencast coals have an unexpectedly high coking power.

Table 6 records analyses of a few samples of opencast coals. It must be remembered that British coals, as normally mined, cover a wide range of types. When these coals are worked at their outcrops, further differences, varying rapidly with the depth of cover and with other conditions, are imposed on the original differences. The figures given in Table 6, therefore, serve only as examples and are not meant to be representative.

TABLE 6
SOME OPENCAST COALS

	Nottinghamshire			South York- shire	South Wales
	(a)	(b)	(c)		
Moisture as received; per cent.	31.0	15.9	—	8	8.4
<i>Analysis on air-dry basis:</i>					
Moisture; per cent.	10.3	7.8	3.4	3.2	4.0
Volatile matter; per cent.	33.4	32.1	33.6	33.6	29.5
Fixed carbon; per cent.	50.0	58.9	59.0	60.7	61.5
Ash; per cent.	6.3	1.2	4.0	2.5	5.0
<i>Analysis on dry, ash-free basis:</i>					
Volatile matter; per cent.	40.0	35.3	36.4	35.6	32.4
Calorific value; B.t.u./lb.	11,200	13,120	14,700	14,780	14,630
Carbon; per cent.	70.7	77.0	82.3	—	—
Hydrogen; per cent.	3.8	4.8	5.3	—	—
Sulphur; per cent.	—	—	—	0.78	0.75

The Nottinghamshire examples are from (a) near the outcrop, (b) from further in, and (c) (for purposes of comparison) from the same seam as worked in a nearby pit. The South Yorkshire and South Wales coals are examples of very good opencast coals.

Highly oxidized opencast coal may not be liable to serious spontaneous heating, but it would be unwise to assume that opencast coal is any less liable than pit coal. The coal is often stored under unfavourable conditions; it is therefore not advisable to relax precautions, especially as better quality coal is reached as the working of the seam progresses.

The precautions for storing opencast coals are not different from those for storing other coals. Occasionally, at sites for the storing of opencast coal, space may not be seriously limited, and then there is no difficulty in confining the height of the stack to 8 feet, which is a compromise between a height low enough to be quite safe and an economic use of the area of the site; but it often happens that ground is more precious, and a deeper heap calls for more vigilance.

The whole area of the site on which the coal is stored should be used at one time so that the coal is built up all over the heap in thin layers. Owing to the great range and uneven mixture of sizes in opencast coal, it is very easy to get a segregation of large coal at the bottom of the stack so that air passes freely through large channels traversing the whole of the base of the stack; and this condition is made worse by occasional "pipes" of large coal running from top to bottom through the heap. No effort should be spared to avoid this very dangerous segregation.

If excavating machinery of a kind that can dig into the heap is available—and in opencast working it often is—precautions need not be so stringent when they can be used. If, when trouble occurs, the heap has to be dug into by hand, everything that can be done to ease this operation is helpful. In particular, if the coal is disposed in long narrow heaps, a heated portion can be isolated by a valley cut across the heap. A long narrow heap is also sometimes easier for certain kinds of excavating machinery to deal with than a broad one, and the spaces between adjacent long heaps afford very necessary access roads to all parts of the stack.

There should be no attempt at ventilation, unless in the very smallest heaps—say of 200 or 300 tons. If the coal can be judiciously compacted in its heap by the traffic of lorries and dumping cars over it, much will be done to impede the percolation of air through the coal.

At appropriate points in the heap, where they will not interfere with traffic handling the coal, pipes, or preferably, rods can be inserted for observations of the temperatures in the heap. A temperature of 70° C. (160° F.) indicates dangerous conditions, especially if the rise in the temperature is occurring at an accelerating rate.

When, according to observations of the temperature in the stack or from other signs, a fire appears imminent, the heated coal must be dug out and used or scattered in a thin layer over adjacent parts of the heap or on neighbouring ground.

If the coal shows signs of heating, the condition may be improved by spraying water in the form of a heavy rain over the affected part; but this practice is not reliable. As has already been said, water is generally ineffective in dealing with fires unless it can be used in prohibitive quantities.

Spontaneous heating may become apparent within six weeks, but if it has not developed within about four months it is not likely to develop at all. There have been indications that if opencast coal has heated and the temperature has been kept down by suitable treatment it is not likely to heat again.

The general nature of stored opencast coal, as regards both quality and size, makes it likely that deterioration will be negligible, provided there is no marked heating

BUNKERS AND CARGOES

Trouble often occurs with the spontaneous combustion of coal in ships' bunkers and cargoes and in factory bunkers. The causes are not different from those operating in ordinary coal stocks, but certain factors have a different emphasis.

The two most important features of difference are, first, that the conditions of ventilation and of the dissipation of heat in a bunker are such that spontaneous combustion can occur in smaller quantities of coal than the 200 tons that is considered to be the minimum quantity in which it occurs in heaps of coal in the open; and this circumstance is aggravated by the second, that in bunkers, by the very fact of their being situated near to, and most often over, the furnaces, the coal is exposed to heating from an extraneous source

Ships' bunkers and cargoes. The occurrence of spontaneous combustion in ships' bunkers and cargoes is a constant source of anxiety to ship owners and underwriters and to ships' masters and crews. It has been a subject of many studies and commissions, one of the most recent investigations being Special Report No. 5 of the Fuel Research Board.⁶

As a result of this investigation the Board of Trade in June, 1930, issued a Notice, No. 106, which was revised and re-issued by the Ministry of Transport in November, 1946. In December, 1922, the Board of Trade also issued Circular 1641 dealing with the surface ventilation of coal cargoes. The Ministry of Transport is at present (1956) considering the revision of both these publications.

The account already given of the causes and prevention of spontaneous combustion is for the best part generally applicable, although it is applicable to British coals and does not necessarily extend without reservation to coals of foreign origin. The coals that find their way into ships' cargoes and especially into ships' bunkers are often of unascertainable origin when they cause trouble; and they are of the most diverse types. In this respect there is little that can usefully be added except to warn that one must be prepared for the worst in the behaviour of coal in ships' bunkers and cargoes and be even more vigilant and stringent in the matter of precautions.

Coal carried in side pockets, and 'tween-deck and bridge-space bunkers, and in holds adjacent to the stokehold is exposed to some warming from an extraneous source, and so the heating is given a start. This risk may in some instances be lessened by constructing a screen wall a few inches from the heated bulkhead so as to leave an insulating space in which air can circulate, otherwise the difficulty is due to an unalterable constructional feature of the ship.

Old coal left in less accessible corners in bunkers may be responsible for a fire, even when fresh coal has been shipped a few times on top of it. It is recommended that bunkers should be completely cleared right out whenever possible, or that the old coal lying in awkward corners should be trimmed towards the bunker door so as to be used first after the bunker has been filled with fresh coal.

In holds and reserve bunkers, chinks in bulkheads (especially in temporary bulkheads) and holes elsewhere allow a local access of air such as to give rise to a dangerous condition. Such holes should be effectively caulked or otherwise stopped.

Many coals, especially those of high rank, like anthracites, and dry steam

and coking coals, are likely to give off gases rich in methane, which is highly inflammable and forms an explosive mixture with air at a concentration as low as about five per cent. In a closed space, such as a ship's hold, this gas can easily accumulate and reach a dangerous concentration. For this reason the Ministry of Transport regulations require that ventilation shall be provided over the surface of, but not into, the coal. It is a wise precaution, further, when a hatch is opened for discharging a cargo of coal, to ensure that no naked lights or smoking are allowed in the hold until the air has had time to clear, in case there may have been some defect or inadequacy in the ventilation. For this reason, too, coal holds and bunkers must have gas-tight bulkheads in order that adjacent holds, lockers, shaft tunnels, accommodation for passengers or crew and similar spaces may not be likewise endangered by gas evolved from the coal passing into them.

Bunkers in Shore Installations. Coal in bunkers in factories and other industrial installations on shore sometimes gives trouble due to spontaneous combustion. Some of the conditions are similar to those prevailing in ships' holds and bunkers.

Apart from the more general causes, spontaneous combustion occurs in land bunkers because the coal is heated somewhat by the plant where it is being consumed, or because old coal has lain long enough in a dead space in the bunker, or because a current of air can pass up through the coal from an imperfect closure at the bunker outlet and thus supply oxygen at a dangerous rate.

Generally, one of these conditions is not sufficient by itself to cause spontaneous combustion. The warming of the coal by adjacent furnaces and other hot plant is probably unavoidable. But if the coal is generally on the move in the bunker, it will not be endangered because none of it will be exposed to the extraneous warming for long enough.

The access of uncontrolled currents of air to coal that is stationary in bunkers becomes dangerous during long shut-down periods with bunkers containing much residual coal. If the valve at the bunker outlet is of a suitable design and is in good condition it may be nearly air-tight; if it is not, some means of making it so must be found and tried. It may be possible, for example, to seal the opening with a luting material plastered around it or with a shallow layer of water in a tarpaulin lashed around the outlet.

A common trouble is spontaneous combustion in bins and bunkers of pulverized fuel. Once it has started the trouble is very obstinate and can rarely be dealt with except by emptying the bunker. The best contribution towards the preventing of it is to pay every attention to minimizing the ingress of air at the bunker outlet.

PREVENTING SEGREGATION AND MAINTAINING FLOW IN COAL BUNKERS

If coal lodges in a dead space in the bunker it may be due to faulty design of the bunker or to coal of a kind that tends to "hang". The contributory fault in the design of the bunker is almost always that the walls do not slope steeply enough for coal to run down freely to the outlet. All bunker walls should slope at an angle of about 60° to the vertical towards an outlet. If the coal contains a large amount of fines, and if it is damp, it may tend to stick and not run freely; in extreme instances, the coal that actually moves may be in a narrow funnel above the outlet, and all the rest of the contents of the bunker may remain stationary. This situation can be dealt with only by ensuring that the stationary coal is moved. This is done by such methods as suit the prevailing conditions, and as are suggested by common sense, for

there are no general principles to apply as a panacea for this trouble, which can be very obstinate. Electric vibrators are sometimes attached to bunker walls near the outlet from the bunker, to keep the coal moving, and if the bunker is of reinforced concrete or heavy steel construction, it may even be expedient to cut out an area of the wall and insert a light steel plate to transmit the effect of the vibrator. It is very important that the vibrator shall be used only when the bunker is being discharged; if the vibrator is used when the coal is stationary, it will compact the coal and make matters worse.

The tendency of coal to arch over a bunker outlet may have to be dealt with by poking or raking at the outlet. But it is less likely to occur if care is taken that the largest coal admitted into the bunker is several times smaller than the bunker outlet itself. Coke tends to arch more than coal, and a bunker outlet should be six to ten times larger than the largest lumps of coke passing through the bunker. *It is well known, however, and must not be overlooked, that the freeing of coal that has stuck in bunkers may endanger the lives of persons descending into the bunkers to attend to it.*

*Segregation and the Uniformity of Feed.*⁷ The larger pieces of a bulk material of a large size-range roll down the slopes on the outside of the cone formed as the material is piled by pouring, or on the inside of the funnel formed as it is discharged from a bunker or hopper. Similarly, large coal runs faster over the top of the smaller coal in inclined chutes, and segregates outwards in fan-tail chutes. *Moving* material thus includes an unrepresentative accumulation of large pieces, and *static* or slowly moving material acquires an unduly high proportion of the finer grades.

This segregation leads to unevennesses in the supply of coal to furnaces and faulty operation in the furnaces, thus contributing to the causes of low efficiency. There is no easy and general method of preventing it; correcting it may be easier, but there is no universal way of doing this either.

Segregation may be reduced when coal is piled, by forming many small cones instead of one large one. This is achieved, in effect, in a hopper, by charging at several points simultaneously instead of at one point; or, where the hopper is filled by a drag-link conveyor, by frequently altering the position at which the conveyor fills the hopper; or by directing the coal flowing into the hopper on to the apices of sheet-steel cones, which throw the coal outward and make it fall over a considerable annular zone instead of on to a very limited central area, this being roughly equivalent to piling the coal in a very flattened cone; or by dividing the hopper with vertical partitions not reaching to the bottom of the hopper (making an "egg-crate" hopper).

The simplest corrective to segregation is the traversing chute used to feed coal into the travelling grate; but it is often not completely satisfactory. Discharging the hopper from several outlets simultaneously—this is the converse of filling it at several points simultaneously—helps to counteract the effect of segregation in the bunker. But these methods of correction have to be adapted to individual circumstances, and almost the only generalization possible is that, where the size of the installation and the space available justify it, the bunker is discharged from several outlets *athwart* the plant to a common entry to a manifold of distributing chutes also *athwart* the plant, each chute being supplied from an entry of its own formed by partitioning the entry common to them all so that their entries are arranged *fore and aft* in the plant. In this way segregation occurring across the plant is corrected by dividing the collective stream of flowing coal in a direction at right angles.

CONCLUSION

The quantity of coal actually in store in Britain fluctuates between 10 and 20 million tons. An estimate of the effective loss of coal due to spontaneous

combustion does not seem to have been attempted, and is probably not possible. In 1686 Dr. Robert Plot, Professor of Chemistry at Oxford University, wrote of the spontaneous combustion of coal in his history of Staffordshire. But today, more than 250 years later, losses due to the faulty stacking of coal must amount to many tens of thousands of tons a year. It should be clearly realized that spontaneous combustion, when it occurs, is a chronic and insidious trouble, that it can be suppressed or even eliminated, that the means of doing this do not offer themselves gratuitously while the coal lies in stock. A little time spent in advance on engineering plans, and a little expenditure of conscious effort at the appropriate times are invaluable if it is to be ensured that the whole of a coal stock is to be available for consumption as originally intended, instead of some of it being burnt on the ground or taken up prematurely for use at an inconvenient moment. The application of principles, quite simple in themselves, such as have been explained, will lead to this end.

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CHAPTER 6

THE CHEMICAL PRINCIPLES OF COMBUSTION
AND GASIFICATION

THE art of *combustion*, or burning, consists in causing chemical reactions that generate heat to take place between the combustible material (generally carbon or hydrogen or compounds of these elements) and oxygen (generally supplied as air) in such a manner that the maximum amount of heat is released. A secondary, but none the less important, branch of the art is to secure the type of flame needed for any particular industrial operation.

Combustion of coal is brought about by the combination of the carbon (C) and hydrogen (H) with the oxygen (O) contained in the air. When carbon burns completely, it results in the formation of a gas, carbon dioxide (CO_2). When carbon burns incompletely it forms carbon monoxide (CO) which when compared with carbon dioxide contains only half the amount of oxygen per unit weight of carbon. The combination of hydrogen with oxygen forms water vapour (H_2O).

Air is a mixture of nitrogen and oxygen in the following approximate proportions :

	<i>by volume</i>	<i>by weight</i>
nitrogen.. ..	79.0 per cent.	76.8 per cent.
oxygen	21.0 per cent.	23.2 per cent.

[Small quantities of carbon dioxide, up to 0.03 per cent. or 0.04 per cent. and of rare inert gases, also present, are included in the figures given for nitrogen.]

So far as combustion is concerned only the oxygen is of value. The nitrogen is a diluent and plays no useful part in the process; in fact it has to be heated up to the temperature of the products of combustion and thus absorbs much of the heat generated.

The object of *gasification* is to cause chemical reactions to take place between carbon, oxygen and steam that will give rise to a combustible gas of the highest practicable calorific value.

Whereas the art of combustion aims at the production of heat, the object of gasification is to convert a solid fuel into a gaseous one which is ultimately burnt to produce heat in another part of the plant or in a separate combustion appliance or used for synthesis of oils or chemical products.

Gasification is used where solid fuel is unsuitable or inconvenient for the process for which heat is required.

COMBUSTION

All ordinary fuels contain carbon, or hydrogen, or both. Some, for example coal, contain both these elements, along with oxygen, in the form of complex substances whose exact chemical nature is still the subject of study and research. Petroleum consists almost solely of hydrocarbons, i.e. compounds of carbon and hydrogen only. Gaseous fuels may contain carbon monoxide, hydrogen, hydrocarbons (all of which are themselves fuels) with or without appreciable proportions of nitrogen, carbon dioxide and even oxygen. Coke consists almost entirely of carbon (except for the ash-forming substances with which it is contaminated).

During combustion, carbon, hydrogen, carbon monoxide and hydrocarbons burn to form carbon dioxide (CO_2) and water vapour (H_2O); heat is always generated in the process. Combustion technique is concerned with the develop-

ment of the maximum quantity of heat from the fuel and with the quantity of heat that escapes unused from the plant.

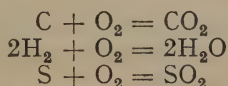
In this chapter the chemistry of combustion and gasification is described, the thermal aspects of the subject being dealt with in Chapter 7.

THE CHEMISTRY OF COMBUSTION

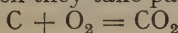
When the substance burnt is coal, coke, oil, gas or other fuel in normal use containing carbon and hydrogen, the products of complete combustion are carbon dioxide and water. Since the combustion is effected with air, the carbon dioxide and water produced are accompanied by a large amount of nitrogen and any excess oxygen that may have been supplied. At the various stages at which they are used or occur the gaseous products of combustion may be called "flue gas" or "waste gas".

As most fuels contain small quantities of sulphur the flue gas may also contain oxides of sulphur, mainly the dioxide (SO_2), but with some trioxide (SO_3) also.

The combination of carbon, hydrogen and sulphur with oxygen may be expressed by the equations:

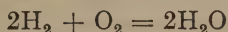


Such equations indicate not only what substances take part in the reaction, but also the proportions in which they take part. Thus the equation,



means that 1 atom of carbon combines with 1 molecule (2 atoms) of oxygen to form 1 molecule of carbon dioxide.

Similarly,



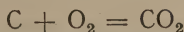
means that 2 molecules (4 atoms) of hydrogen combine with 1 molecule (2 atoms) of oxygen to give 2 molecules of water.

The number of atoms of each of the several elements on each side of any chemical equation must be equal.

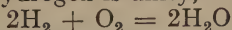
A molecule is the smallest particle of any particular element or compound that can exist alone and possess its chemical and physical properties. Most gases that are elements exist as molecules containing two atoms, indicated in the formula for the molecule; thus the formula for oxygen as we ordinarily know it—oxygen in the air—is O_2 and that of hydrogen is H_2 .

All atoms of the same elements may be considered to have the same weight and the relative weights of the atoms of the different elements are known, the weight of the hydrogen atom being taken as approximately 1.0. It follows that these equations show also the proportions by weight in which the various substances take part in each reaction.

For example, since the atomic weight of carbon is 12 and that of oxygen is 16, the equation



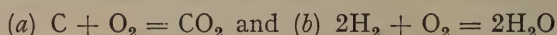
also indicates that 12 parts by weight of carbon combine with 2×16 i.e. 32 parts of oxygen to give $12 + 2 \times 16$ i.e. 44 parts of carbon dioxide. Similarly, since the atomic weight of hydrogen is unity,



implies that 2×2 i.e. 4 parts by weight of hydrogen combine with 2×16 i.e. 32 parts of oxygen to give $2 \times (2 + 16)$ i.e. 36 parts by weight of water.

"Parts by weight" may be grams, kilograms, pounds, tons and so forth, provided the same units are used throughout.

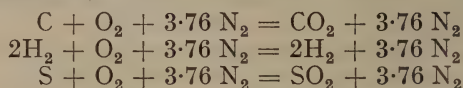
Equations such as these can also be used to determine the relative volumes of the gases taking part in the reactions since equal volumes of gases at the same temperature and pressure contain equal numbers of molecules. Thus the equations,



indicate (a) that when carbon is burnt completely one volume of oxygen gives rise to one volume of carbon dioxide;

and (b) that two volumes of hydrogen, when burnt, combine with one volume of oxygen to produce two (not three) volumes of steam.

Since air may for all practical purposes be taken to consist of 21 per cent. (by volume) of oxygen (O_2) and 79 per cent. (by volume) of nitrogen (N_2) one volume of oxygen in air is accompanied by 79/21 i.e. 3.76 volumes of nitrogen, and from the point of view of the combustion engineer these equations are more correctly written:



The nitrogen takes no chemical part in the reactions, being merely a useless "passenger", but it is there throughout and, as already stated, uses up valuable heat when it is part of a hot flue gas.

In these examples it has been assumed that the gases are all measured at the same temperature and pressure. If they are not at the same temperature and pressure the volumes should be corrected according to the equation,

$$\frac{PV}{T} = \text{constant}$$

where V is the volume, P the absolute pressure and T the Absolute temperature.

Thus if the volume of a certain amount of a gas, measured at $t_1^\circ \text{C.}$ and p_1 mm. mercury (Hg)* pressure, is V, its volume at $t_2^\circ \text{C.}$ and p_2 mm. pressure will be

$$V \times \frac{t_2 + 273}{t_1 + 273} \times \frac{p_1}{p_2}$$

Similarly, using Fahrenheit degrees, and pressures measured in inches, if the initial temperature and pressure are $t_1^\circ \text{F.}$ and p_1 in. respectively, and if the new temperature and pressure are $t_2^\circ \text{F.}$ and p_2 in., the new volume will be

$$V \times \frac{t_2 + 460}{t_1 + 460} \times \frac{p_1}{p_2}$$

Since equal volumes of gas contain the same number of molecules, the molecular weights of all gases, expressed in the same units of weight, occupy the same volume. It has been determined experimentally that within certain limits the molecular weight of any gas expressed

- (a) in grams, occupies 22.4 litres at 0°C. and 760 mm. Hg. pressure;
- (b) in pounds, occupies 359 cubic feet at 32°F. and 30 in. Hg. or 379 cubic feet at 60°F.

the gas being dry in every case. These amounts are known as the *gramme-molecular weight* and the *pound-molecular weight*, respectively. If the gas is saturated with water vapour at 60°F. the volume occupied at a total pressure of 30 in. Hg is 385 cubic feet.

The atomic weights and (for gases only) the molecular weights of some of the more common elements and compounds are given in Table 1.

* Hg is the chemical symbol for the element mercury and is commonly used in combustion engineering as a convenient shorthand expression for the full name. (See Chapter 17.)

TABLE 1

	Symbol for atom of element	Atomic weight	Formula of molecule	Molecular weight (approx.)
Hydrogen.. .. .	H	1	H ₂	2
Carbon	C	12	—	—
Nitrogen	N	14	N ₂	28
Oxygen	O	16	O ₂	32
Sulphur	S	32	—	—
Water vapour	—	—	H ₂ O	18
Carbon monoxide	—	—	CO	28
Carbon dioxide	—	—	CO ₂	44
Sulphur dioxide	—	—	SO ₂	64
Methane	—	—	CH ₄	16

Sufficient data have now been given to calculate the quantity of air theoretically required for the combustion of 1 lb. of coal, coke, or oil, and the composition of the products of combustion. Certain gases, however, do not conform exactly with the laws given above, which refer to "perfect" gases, and this may lead to errors. More precise figures for some of the constants frequently used in combustion calculations are given in Tables 2 and 3.

TABLE 2

1 lb. of carbon, hydrogen or sulphur (as the case may be) requires for the conversion, during combustion, of				
C to CO ₂	H ₂ to H ₂ O	S to SO ₂	C to CO	of oxygen
2.664 lb.	7.937 lb.	0.9979 lb.	1.332 lb.	
the		process	involving	
8.820 lb.	26.27 lb.	3.303 lb.	4.410 lb.	of nitrogen in the air used
the weight of air used being thus				
11.48 lb.	34.21 lb.	4.301 lb.	5.742 lb.	
and		the	yields	being
CO ₂	H ₂ O	SO ₂	CO	
3.664 lb.	8.937 lb.	1.998 lb.	2.332 lb.	
along with the following weights of nitrogen (as above)				
8.820 lb.	26.27 lb.	3.303 lb.	4.410 lb.	
The	volumes involved,	at 60° F.	and 30 in. Hg,	are
CO ₂	H ₂ O*	SO ₂	CO	
31.52 cu. ft.	187.7 cu. ft.	11.57 cu. ft.	31.52 cu. ft.	
along		with		
118.5 cu. ft.	352.8 cu. ft.	44.36 cu. ft.	59.23 cu. ft.	of nitrogen

* Water vapour. At this temperature and pressure, the water would actually be liquid and occupy a very small volume.

Although on cooling to the specified standard temperature the steam in the products of combustion will have condensed to (liquid) water, it is convenient in many calculations to assume that it occupies the same volume as it would if it remained a gas; that volume is, therefore, given in Tables 2 and 3.

The mol system

In practically all combustion calculations it is sufficiently accurate to take the atomic and molecular weights of the substances to be those given in Table 1, and to assume that all the gases obey the laws for a perfect gas. It is then possible to use a method of calculation which is comparatively simple and only

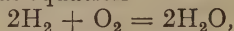
TABLE 3

Gas	DENSITY lb. per cu. ft. at 60° F. and 30 in. Hg.	SPECIFIC VOLUME cu. ft. per lb. at 60° F. and 30 in. Hg.
H ₂	0.00533	187.6
O ₂	0.08457	11.82
N ₂ *	0.07446	13.43
CO ₂	0.1163	8.600
SO ₂	0.1727	5.790
H ₂ O	0.04761	21.00
CO	0.07400	13.51
CH ₄	0.04237	23.60
Air	0.07657	13.06

* Atmospheric nitrogen (i.e. with traces of rare gases).

necessitates a knowledge of Table 2 and the volume occupied by the molecular weight of a gas at a standard temperature and pressure. The principle is to work throughout the calculation with the weights of each chemical compound expressed in units of its molecular weight in some system of units. The weight is given as a certain number of *mols*. For example, for calculations in pounds, 12 lb. of carbon are equal to 1 mol of carbon as the molecular weight of carbon is 12. Similarly, 12lb. of hydrogen are equal to 6 mols of hydrogen as the molecular weight of hydrogen is 2.

If we consider the chemical equation



we have seen that this shows that 4 lb. of hydrogen combine with 32 lb. of oxygen to give 36 lb. of water, and so we can say that 2 mols of hydrogen combine with 1 mol of oxygen to give 2 mols of water. Thus the coefficients of the terms in the chemical equation give directly the number of mols of each compound.

Also, as the molecular weight of every gas occupies the same volume, it is a simple matter to convert a gas composition expressed in mols to one expressed in units of volume, and *vice versa*. For example, 100 cubic feet of air contain 79 cubic feet of nitrogen and 21 cubic feet of oxygen. Now we know that at 60° F. and 30 in. Hg pressure the molecular weight in pounds, i.e. 1 mol, of any gas occupies 379 cubic feet, 79 cubic feet of nitrogen weigh $\frac{79}{379}$ mols, and 21 cubic feet of oxygen weigh $\frac{21}{379}$ mols. Thus the ratio of nitrogen to oxygen in air, both being expressed in mols, is also 79 to 21. From this it can be seen that the proportion by volume of the constituents of a gaseous mixture is equal to the proportion when each constituent is expressed in mols. (In Chapter 7, "Gas Producer Reactions", the volume 358.7 cu. ft. is quoted. That volume, as explained, is the volume measured at 32° F. and 14.7 lb./sq. in. abs.)

The ease with which one can change from mols to weights in lb. or grams, or to volumes in cubic feet or litres and *vice versa* simplifies most combustion calculations and this method is used in some of the examples in the following pages.

CALCULATION OF THE QUANTITY OF AIR THEORETICALLY REQUIRED FOR THE COMPLETE COMBUSTION OF COAL OR OIL

A method of calculating the quantity of air required for the complete combustion of a coal is illustrated by the following example:

Chemical composition of coal sample

				per cent. by weight
Carbon	..	..	..	74.0
Hydrogen	..	..	..	5.0
Oxygen	..	..	..	5.0
Nitrogen	..	..	..	1.0
Sulphur	..	..	..	1.0
Moisture	..	..	..	9.0
Ash	..	..	..	5.0
				100.0

Using the figures given in Table 2 the amount of oxygen required by each constituent of 1 lb. of fuel is shown below:

Constituent			Weight per lb. of fuel	Weight of oxygen required per lb. of fuel
			lb.	lb.
C	..	..	0.74	$0.740 \times 2.664 = 1.97$
H ₂	..	..	0.05	$0.050 \times 7.937 = 0.40$
O ₂	..	..	0.05	— 0.05 (initially present)
N ₂	..	..	0.01	—
S	..	..	0.01	$0.010 \times 0.9979 = 0.01$
H ₂ O	..	..	0.09	—
Ash	..	..	0.05	—

Total weight of oxygen required per lb. of fuel = 2.38-0.050, i.e. 2.33 lb.

The above results can also be obtained using the mol method. The amount of each constituent is first converted to a mol basis by dividing it by its molecular weight. The total number of mols of oxygen required for the complete combustion of 1 lb. of fuel can then be readily obtained by summation and from this the weight and volume of oxygen required can be calculated. The whole calculation is shown in the following table.

Constituent			Weight per lb. of fuel	Mols per lb. of fuel	Mols of oxygen required per lb. of fuel
			lb.		
C	..	..	0.74	$\frac{0.74}{12} = 0.0617$	$1 \times 0.0617 = 0.0617$
H ₂	..	..	0.05	$\frac{0.05}{2} = 0.0250$	$\frac{1}{2} \times 0.0250 = 0.0125$
O ₂	..	..	0.05	$\frac{0.05}{32} = 0.0016$	— 0.0016 (initially present)
N ₂	..	..	0.01	—	—
S	..	..	0.01	$\frac{0.01}{32} = 0.0003$	$1 \times 0.0003 = 0.0003$
H ₂ O	..	..	0.09	—	—
Ash	..	..	0.05	—	—

Total number of mols of oxygen required per lb. of fuel = 0.0729; thus weight of oxygen required = 32 × 0.0729 = 2.33 lb.

Air consists of 23.2 parts of O_2 and 76.8 parts of N_2 by weight. Therefore the total air required $= 2.33 \times \frac{100}{23.2} = 10.0$ lb. (This calculation is referred to in Chapter 7, Excess Air.)

At $60^\circ F.$ and 30 in. Hg, 1 lb. of air occupies 13.06 cubic feet. Hence volume of air required $= 10.0 \times 13.06 = 131$ cubic feet approximately.

As air consists of 21.0 per cent. of O_2 and 79.0 per cent. of N_2 , the 131 cubic feet of air consists of 27.5 cubic feet of O_2 and 103.5 cubic feet of N_2 again ignoring traces of other gases present in the atmosphere.

CALCULATION OF THE VOLUME AND COMPOSITION OF THE PRODUCTS OF COMBUSTION

Volume

The total volume of the products of combustion can be derived by using the figures in Tables 2 and 3 to calculate the volume of the combustion gases made by burning each combustible constituent of the fuel and adding the volume of nitrogen also present along with the oxygen in the air used. The method of calculation is shown in Table 4, using the same coal as that for which the volume of air was calculated in the last section.

TABLE 4

Constituent	Weight per lb. of fuel	Product	Volume
	lb.		cu. ft.
C	0.74	CO_2	$0.740 \times 31.52 = 23.3$
H	0.05	H_2O	0.050×187.7
* H_2O	0.09	H_2O	0.090×21.00
O	0.05	—	} = 11.3†
N	0.01	N_2	$0.010 \times 13.43 = 0.134$
S	0.01	SO_2	$0.010 \times 11.57 = 0.116$
Ash	0.05	—	
Nitrogen in air for combustion			= 103 cubic feet
Total volume of gas (wet basis)			= 138 cubic feet
Total volume of gas (dry basis) = 138 — 11.3			= 127 cubic feet

* 9 per cent. of moisture originally present and remaining subsequently as moisture (H_2O).

† 11.3 per cent. total H_2O , condensing ultimately to (liquid) moisture.

The results obtained in the table can also be calculated by the mol method. The relevant calculations are as follows:

Constituent	Mols per lb. fuel	Product	Mols of product per lb. fuel
C	0.0617	CO_2	$1 \times 0.0617 = 0.0617$
H	0.0250	H_2O	1×0.0250
H_2O	0.0050	H_2O	0.0050
O	0.0016	—	} = 0.0300
N	0.0007	N_2	0.0007
S	0.0003	SO_2	$1 \times 0.0003 = 0.0003$
Total number of mols of product per lb. of fuel ..			0.0927

Now as the proportions of the constituents, by mols, of a gaseous mixture is equal to their proportions by volume, 100 mols of air contain 21.0 mols of oxygen and 79.0 mols of nitrogen. Thus from the previous calculation the air theoretically required to burn 1 lb. of fuel contains

$$0.0729 \times \frac{79.0}{21.0} = 0.2740 \text{ mols of nitrogen}$$

Thus the number of mols of wet gas per 1 lb. of fuel= $0.0927+0.2740=0.3667$, so the volume of wet gas per 1 lb. of fuel at 60°F . and 30 in. Hg pressure equals 0.3667×379 , i.e. 139 cu. ft. Similarly, the number of mols of dry gas per pound of fuel equals $(0.0927-0.0300)+0.2740$, i.e. 0.3367, and so the volume of dry gas per pound of fuel, at 60°F . and 30 in. Hg equals 0.3367×379 , i.e. 128 cu. ft.

If *excess air* is used, the composition of the products of combustion will be obtained by adding the appropriate quantities of oxygen and nitrogen in that excess air to the volumes already determined. Thus if 50 per cent. of excess air (i.e. an extra 50 per cent. of the air theoretically required for combustion

or $\frac{131}{2}$ i.e. 65.5 cu. ft. containing 13.8 cu. ft. of $\text{O}_2+51.7$ cu. ft. of N_2) is added to the products of combustion, the total volume of the dry products will be $127.3+65.5$, i.e. 193 cu. ft. (approx.) of which 13.8 cu. ft. will be O_2 and $103+51.7$, i.e. 155 cu. ft. (approx.) will be N_2 . The analysis of the flue gas with 50 per cent. of excess air is shown in column 3 of the table given below.

It will be noted that adding 50 per cent. of excess air has lowered the percentage (but not the actual *amount*) of CO_2 from 18.3 to 12.1. In practical combustion extra air (excess air) is always needed, i.e. in addition to what is theoretically required.

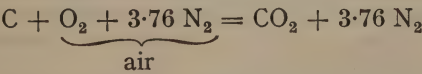
COMPOSITION OF PRODUCTS OF COMBUSTION

The percentage composition of the products of combustion is derived by dividing the volume of each particular gas by the total volume. At high temperatures the water will be present as a gas but in the conditions under which analyses are done (e.g. Orsat) the water condenses to the liquid form and the results are expressed on the dry basis, i.e. excluding moisture formed during combustion as well as moisture previously existing in the fuel. The analyses of the flue gas on a wet basis and on a dry basis will be as shown in Columns 1 and 2 below.

Constituent	1	2	3
	In wet gas	In dry gas	In dry gas with 50 per cent. excess air
	per cent.	per cent.	per cent.
CO ₂ ..	$23.3/138 \times 100 = 16.9$	$23.3/127 \times 100 = 18.3$	$23.3/193 \times 100 = 12.1$
SO ₂ ..	$0.116/138 \times 100 = 0.1$	$0.116/127 \times 100 = 0.1$	$0.116/193 \times 100 = 0.1$
H ₂ O ..	$11.3/138 \times 100 = 8.2$	—	—
N ₂ ..	$103/138 \times 100 = 74.8$	$103/127 \times 100 = 81.6$	$155/193 \times 100 = 80.6$
O ₂ ..	—	—	$13.8/193 \times 100 = 7.2$

The figures 138, 127 and 193 are derived as follows: by reference to Table 4 138 and 127 are the respective volumes of wet and dry gas involved. Using 50% excess air (i.e. 50% of 131 cu. ft.), the total volume of dry gas becomes $131\div 2+127$, i.e. 193 cu. ft.

In the complete combustion of pure carbon in air to form carbon dioxide according to the equation previously given,



the oxygen of the air is entirely replaced by CO_2 , volume for volume; consequently the proportion of CO_2 in the combustion gases is the same as that of O_2 in the air, viz. 21.0 per cent. When, however, the fuel contains other combustible constituents, e.g. hydrogen and sulphur, the *percentage* of CO_2 in the

products of combustion will be less owing to the presence of sulphur dioxide, additional nitrogen and water vapour.

In practice the sulphur dioxide will be recorded as carbon dioxide, so that the only apparent diluent in the dry combustion products will be nitrogen; but the amount of nitrogen and its effect upon the percentage of CO_2 will be determined by the percentage of hydrogen in the fuel. This effect is well illustrated in the last column of the table given above.

COMBUSTION DATA FOR TYPICAL SOLID AND LIQUID FUELS

Table 5 gives figures for a number of typical solid and liquid fuels burned with the exact amount of air required for their combustion. The four coals are those referred to in Table 3, Chapter 7.

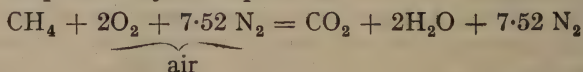
TABLE 5
COMBUSTION DATA FOR SOME TYPICAL BRITISH FUELS.

Fuel	Air required per lb. of fuel		Vol. of waste gases: cu. ft.*	Calculated wet waste gas analysis			CO_2 in dry waste gas Per cent.
	lb.	cu. ft.*		CO_2 Per cent.	N_2 Per cent.	H_2O Per cent.	
Non-coking coal: 40% V.M.; 5% ash; 10% moisture ..	8.68	113	122	17.2	73.8	9.0	18.9
Coking coal: 30% V.M.; 5% ash; 2% moisture	10.75	140	147	17.3	75.8	6.9	18.6
Low-V.M. coal: 18% V.M.; 4% ash; 1% moisture ..	11.28	148	152	18.0	76.6	5.4	19.0
Anthracite: 4% V.M.; 3% ash; 1% moisture	11.34	150	152	18.9	77.4	3.7	19.6
Coke: 1% V.M.; 7% ash; 2% moisture	10.22	134	135	20.2	78.2	1.6	20.5
C.T.F. 250	12.26	160	166	17.1	76.2	6.7	18.3
Fuel oil (C:86%; H:12%) ..	14.0	184	194	14.1	74.5	11.4	15.9

* Volumes at 60°F. and 30 in. Hg.

CALCULATION OF THE COMPOSITION OF THE FLUE GASES FROM GASEOUS FUELS

The composition of flue gases from a gas such as coal gas can be calculated on similar lines, but the fundamental combustion equations are more complicated and are applied on a volume basis only. As an example, the combustion of methane is expressed by the equation:



As will be evident from previous explanations, the interpretation of this equation, in terms of waste gas analysis, is that when 1 cubic foot of methane is burned with air, it requires 2 cubic feet of oxygen (and consequently 9.52 cubic feet of air) and it forms as waste gas, 1 cubic foot of carbon dioxide, 2 cubic feet of water vapour and 7.52 cubic feet of nitrogen, all assumed to be measured at the same temperature.

Taking as an example the analysis of horizontal retort gas given in Chapter 3 (Table 1), the combustion reactions and their resultant products can be summarized as shown below, noting that each cubic foot of oxygen required is accompanied by 3.76 cubic feet of nitrogen.

Constituent of fuel gas	Combustion reaction	Cu. ft. per cu. ft. of constituent in first column			
		O ₂ req'd	N ₂ (in air)	CO ₂ formed	H ₂ O formed
Hydrogen—H ₂ ..	2H ₂ + O ₂ = 2H ₂ O	0.5	1.88	—	1.0
Methane—CH ₄ ..	CH ₄ + 2O ₂ = CO ₂ + 2H ₂ O	2.0	7.52	1.0	2.0
*Hydrocarbons—C _n H _m taken as C ₃ H ₈ ..	2C ₃ H ₈ + 9O ₂ = 6CO + 6H ₂ O	4.5	16.92	3.0	3.0
Carbon monoxide—CO	2CO + O ₂ = 2CO ₂	0.5	1.88	1.0	—
Carbon dioxide—CO ₂	None	—	—	—	—
Oxygen—O ₂ ..	Assists in burning the combustible	—	—	—	—
Nitrogen—N ₂ ..	None	—	—	—	—

* Unsaturated hydrocarbons whose composition is not known are usually accorded the general formula C_nH_m; for the purposes of calculation they are assumed to have an average composition corresponding to C₃H₈.

The calculation for 100 cubic feet of gas then proceeds as follows:

Constituent	Per cent. by vol.	O ₂ required for combustion cu. ft.	Products cu. ft.		
			CO ₂	H ₂ O	N ₂
H ₂	52.0	26.0	—	52.0	97.8
CH ₄	30.0	60.0	30.0	60.0	225.6
*C _n H _m taken as C ₃ H ₈	3.6	16.2	10.8	10.8	60.9
CO	8.0	4.0	8.0	—	15.0
CO ₂	2.0	—	2.0	—	—
O ₂	0.4	—0.4	—	—	—1.5
N ₂	4.0	—	—	—	4.0
Volume per 100 cu. ft. of town gas cu. ft.		105.8	50.8	122.8	401.8

The oxygen is provided from air; thus to provide 105.8 volumes of oxygen

$105.8 \times \frac{100}{21.0}$ i.e. 503.8 volumes of air are required.

In other words, the air required for the combustion of 100 volumes of gas is 503.8 volumes.

Thus 1 cubic foot of gas requires theoretically for combustion 5.038 cubic feet of air.

The products from 100 cubic feet of gas and 503.8 cubic feet of air, both measured at 60° F. and 30 in. Hg, will be:

	Volume, the water assumed to be uncondensed : cu. ft.	Per cent. by volume
CO ₂	50.8	8.8
H ₂ O (steam)	122.8	21.3
N ₂	401.8	69.9
Total	575.4	100.0

The volume of products formed when 1 cubic foot of this gas is completely burnt with 5.038 cubic feet of air is therefore 5.754 cubic feet at 60°F. and 30 in. Hg.

The volume of products from 100 cubic feet of gas is, therefore, on the dry basis:

CO ₂	50.8 cubic feet
N ₂	401.8 ..
Total	452.6 ..

The volume of products of combustion (dry) from 1 cubic foot of this sample of town gas with 5.038 cubic feet of air is therefore 4.526 cubic feet.

The percentage of CO₂ is $\frac{50.8 \times 100}{452.6} = 11.2$ per cent.

The calculation can be extended to include excess air in the same way as for coal in the example previously given.

Particulars of the combustion of some industrial gases are contained in Table 6.

TABLE 6
COMBUSTION PRODUCTS OF SOME INDUSTRIAL GASES.

	Typical Coal gas	Typical producer gas		Typical blast furnace gas
C.V.—B.t.u./cu. ft. gross ..	475	163	132	92
Cu. ft. air required for 1 cu. ft. gas (theoretical)	4.06	1.28	1.00	0.69
Products of combustion from 1 cu. ft. of gas:	cu. ft.	cu. ft.	cu. ft.	cu. ft.
CO ₂	0.50	0.36	0.34	0.38
H ₂ O	0.97	0.18	0.12	0.02
N ₂	3.27	1.53	1.34	1.14
Total	4.74	2.07	1.80	1.54
Theoretical CO ₂ content as analysed, i.e. on dry gas ..	per cent. 13.3	per cent. 19.2	per cent. 20.5	per cent. 24.9

THE CHEMISTRY OF GASIFICATION

A fuel bed may be shallow or deep. If the bed is very shallow, the carbon burns wholly to carbon dioxide. With a deeper bed the carbon dioxide first formed, and water vapour present in the incoming air are brought into contact with red-hot carbon and certain other reactions occur, to promote which is the function of gasification. A deep fuel bed naturally offers the best conditions for these further reactions, though they may occur to a lesser extent in the shallow fuel bed of the boiler furnace. A fuel bed of the order of 3 feet deep or more is used for gasification for the manufacture of producer gas.

It is convenient to consider these reactions as confined to several zones (Fig. 1) though they overlap into the zones above and below. The gases passing into the base of the fuel bed may comprise air and steam and when reacting in the fuel bed give rise to chemical and thermal effects of great importance. The significance of the thermal reactions here referred to is explained in Chapter 7.

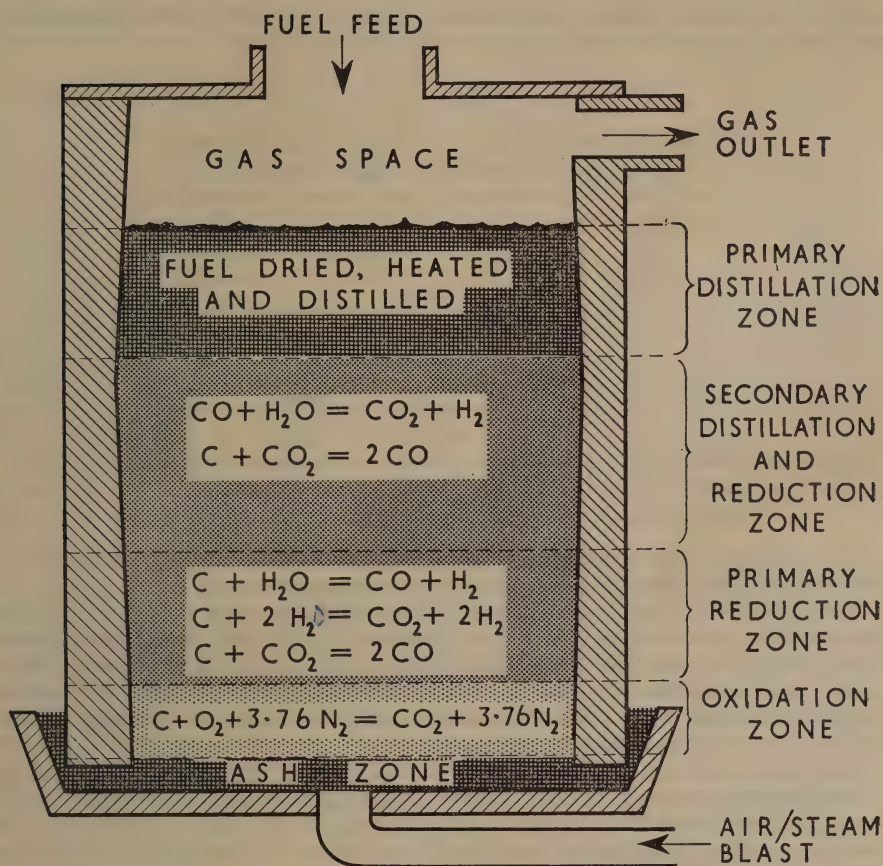
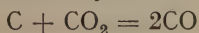


FIG. 1. Chemical reactions in a gas producer.

The ash zone at the base of the fuel bed serves to protect the grate from the intense heat and helps to distribute the air and steam over the bed.

Above the ash zone is the oxidation zone, at which the reaction $C + O_2 = CO_2$ proceeds, free oxygen disappearing about 4 to 5 inches above the top of the layer of ash. This reaction generates heat and provides practically the whole of the heat required for the subsequent gasification reactions.

The CO_2 , accompanied by nitrogen and steam, travels upwards into the reducing zone. Here a reaction between CO_2 and carbon takes place resulting in the production of the combustible gas, carbon monoxide, thus:



This reaction (unlike most other combustion reactions) results in the *absorption* of heat. Heat must be supplied to the substances taking part in it; heat is absorbed from the red hot fuel bed and its surroundings, the temperature falls, and the reaction "slows down". Consequently the extent to which this reaction continues depends upon the temperature, and upon the time available. Equilibrium values, which are attained only by sustained contact of dry air with carbon in the absence of other disturbing factors, are given in Table 7.

It will be seen that the percentage of CO produced increases with rise in temperature. In practice, although a temperature of 800° – 900° C. would appear

to give a satisfactorily high percentage of CO, higher temperatures are generally required to enable the reaction to proceed at a useful rate.

TABLE 7
EQUILIBRIUM FIGURES FOR REACTION BETWEEN
CARBON DIOXIDE AND CARBON

Temperature		Composition of gas		
° C.	° F.	CO ₂	CO	N ₂
		per cent.	per cent.	per cent.
600	1,112	13.76	11.74	74.50
700	1,292	5.85	24.95	69.20
800	1,472	1.35	32.30	66.35
900	1,652	0.30	34.10	65.60
1,000	1,832	0.08	34.42	65.50
1,100	2,012	0.03	34.52	65.45
1,200	2,192	0.01	34.56	65.43

The velocity of chemical reactions increases very rapidly with rise in temperature and is correspondingly low at lower temperatures.

Owing to the absorption of heat by the reactions which take place, as the gases pass upwards through the reduction zones of the producer, the temperature of the fuel bed falls; hence the velocity of the reactions taking place is lower than expected. The result is that true equilibrium conditions are not usually attained with times of contact and temperatures common in the reduction zone of industrial producers.

Since the reactions in the combustion zone give predominantly CO₂, the gas formed at temperatures of 600°–1,000° C. contain in practice more CO₂ than is indicated by Table 7. At higher temperatures of the order of 1,200° C. the reaction might proceed substantially to completion, but owing to the influence of other factors this rarely occurs.

In a producer operated or "blown" with dry air, the presence of CO₂ in the producer gas represents a waste of fuel, because some carbon has been burnt completely to CO₂ and sensible heat has been liberated within the producer instead of subsequently in the furnace where the producer gas is burnt. When steam is added to the blast, however, not all the CO₂ represents waste, as will be shown below. In any case, it is clearly desirable that the temperature in the gasification zone be as high as possible. On the other hand the gas outlet temperature should be as low as possible in order to avoid excessive loss of sensible heat if the gas is cooled before being used.

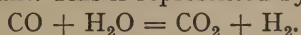
At temperatures above about 800° C. steam reacts with carbon according to the equation: $C + H_2O = CO + H_2$ with absorption of heat. (See Equations 1, 2, Chapter 3). Steam is, therefore, added to the blast partly to moderate the temperature in the combustion zone in order to reduce clinker formation and partly to utilize the gasification zone more effectively by generating additional CO and H₂. The higher temperature at which the reaction takes place the greater is the extent to which the steam is decomposed by the carbon and, therefore, the greater is the amount of CO and H₂ formed, until at temperatures of the order of 1,100° C. the steam is almost completely decomposed. The effect of temperature on the reaction when steam only is passed over or through red-hot carbon is illustrated by the experimental figures given in Table 8.

TABLE 8. THE ACTION OF STEAM ON CARBON: ANALYSES OF GASES¹

Temperature		Steam decomposed	CO ₂	CO	H ₂
° C.	° F.				
674	1,245	<i>per cent.</i> 8.8	<i>per cent.</i> 29.8	<i>per cent.</i> 4.9	<i>per cent.</i> 65.2
838	1,540	41.0	22.9	15.1	61.9
954	1,750	70.2	6.8	39.3	53.5
1,010	1,850	94.0	1.5	49.7	48.8
1,125	2,057	99.4	0.6	48.5	50.9

These figures do not correspond to the attainment of chemical equilibrium, but give some indication of the extent to which the reaction may proceed under practical conditions. In the case of a producer where the steam is mixed with a large volume of air, the relative proportions of CO₂, CO, and H₂ in the products would differ considerably from the above, but the general trend with changing temperatures would be the same.

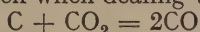
In the temperature range 600–1,000° C. another reaction, which takes place between CO and undecomposed steam and is known as the water-gas “shift” reaction, becomes important. This is represented by the equation:



It will be noticed when steam is present the CO₂ formed according to the equation does not represent a waste of carbon, because the CO which reacts with the steam is replaced by its own volume of hydrogen, which has approximately the same calorific value and the final gas will have the same heat content on a volume basis. It should be noted, however, that the dilution of the final *dry* gas by the CO₂ formed in this reaction has the undesirable effect of lowering its calorific value. As in the case of dry blast operation, a high yield of combustible gases requires a high temperature in the reduction zone, where CO and H₂ are formed with absorption of heat. The necessary heat is provided wholly by the combustion reaction in the oxidation zone, and this heat must

(a) heat up the fuel in the reduction zone to the necessary temperature, and (b) compensate for the absorption of heat in the reduction of CO₂ and steam.

All the reactions are equilibrium reactions, and under suitable conditions may proceed in the reverse direction to those here indicated. At any temperature there is an equilibrium composition of the substances taking part in the reaction which is the more closely approached as time and temperature are adequate; an example was given when dealing with the reaction



These reactions are summarized in Fig. 1; their thermal effects are summarized in Fig. 7, Chapter 7.

At the top of the fuel bed, the fresh fuel (if coal is used) is distilled, permanent gases, water and tar being added to the gases leaving the fuel bed. Any water contained in the incoming fuel is evaporated at this stage.

The quantity of steam used has an important influence on the reactions. This is discussed in detail in the chapter on gas producers (Chapter 18). It is obviously important that as much of the steam as possible shall be converted into gas, and in its conversion into gas shall produce as much CO and H₂ as possible.

The net results of the various reactions here described can be followed experimentally. The course of the changes that take place has been determined by examination of gas samples withdrawn from closely adjacent sampling points in the fuel bed of a coke-fired producer, Table 9.

TABLE 9. COMPOSITION OF GASES IN THE FUEL BED OF
A GAS PRODUCER²

Zone	Height of sampling point above grate in.	Composition of gases—Per cent. by vol.				
		O ₂	CO ₂	CO	H ₂	H ₂ O
Ash	5	18.4	—	—	—	13.4
Oxidation ..	7.5	—	17.6	2.8	—	13.1
Primary reduction	10	—	11.5	12.2	—	12.2
“ “	15	—	7.2	20.4	4.0	8.1
“ “	20	—	5.9	23.3	7.0	4.7
Secondary reduction	30	—	4.6	25.6	8.2	3.5
Top of fuel bed ..	40	—	4.7	27.0	8.5	2.7

If, as in some older producers, air only is blown through the fuel bed, the resulting gas is similar to blast furnace gas, though containing less CO₂ and proportionately more CO. (See also Chapter 18, Producer Gas.)

REFERENCES.

¹ HARRIES, J. *für Gasbeleuchtung* 1894, 4, 82.

² HASLAM & RUSSELL, *Fuels and Their Combustion*. McGraw-Hill & Chapman and Hall. (Fig. 214, p. 553.)

See also References at ends of Chapters 2 and 3.

CHAPTER 7

HEATING EFFECTS IN COMBUSTION AND GASIFICATION

PHYSICAL CONSTANTS

FIGURES of physical constants required in fuel technology are given in "Technical Data on Fuel"¹. Only such figures are given here as are required for an explanation of the subject.

DATUM CONDITIONS

In making thermal calculations it is necessary to select a temperature from which to start. For steam tables the temperature selected is 32° F. (0° C.) on the ground that below that temperature water solidifies, and 32° F. is the lowest temperature at which water can normally exist as a liquid.

For some thermochemical calculations the datum temperature used is 0° C. (32° F.) but for most industrial combustion calculations 60° F. is used as a datum.

MEASUREMENT OF QUANTITY OF HEAT

Quantity of heat is defined as, and measured by, the amount of heat that is required to raise the temperature of a given weight of water through a given temperature range.

The pound-Fahrenheit system measures heat in terms of British Thermal Units (B.t.u.). One B.t.u. is the quantity of heat required to raise the temperature of water through one Fahrenheit degree. Since the heat capacity of water is not exactly the same at all temperatures, a more precise definition of this heat unit is the amount of heat required to raise the temperature of 1 lb. of water from 60° to 61° F. Another unit, the *mean B.t.u.*, is 1/180 of the heat required to raise the temperature of 1 lb. of water from 32° F. to 212° F. (without conversion to vapour). A larger unit used in industry and especially by the gas industry is the *Therm*, i.e. 100,000 B.t.u.

Using the Metric System, the basic heat unit is the calorie, or gramme calorie, which is the amount of heat required to raise the temperature of 1 gramme of water through one Centigrade degree, generally from 15° C. to 16° C. The *mean calorie* is one hundredth of the amount of heat required to raise the temperature of one gramme of water from 0° C. to 100° C. (without vaporization). 1,000 calories equal one kilogramme calorie or Calorie.

Another unit, the pound-Centigrade unit, or Centigrade Heat Unit, "C.H.U.", is sometimes used. It is the amount of heat required to raise the temperature of 1 lb. of water through one Centigrade degree.

These units are inter-related as follows:

1 B.t.u.	=	252 calories	=	0.556 C.H.U.
1 keal	=	1,000 calories	=	3.968 B.t.u.
1 C.H.U.	=	1.8 B.t.u.	=	453.6 calories
1 Therm	=	100,000 B.t.u.	=	25,200 keal

Heat, work and energy are closely inter-related, in obedience to the Law of Conservation of Energy. The reader is referred to the Tables in Appendix A showing some of these relationships.

SPECIFIC HEAT

The specific heat of a substance is the ratio of (a) the quantity of heat required to raise the temperature of unit weight of the substance through unit

temperature range (one degree) to (b) that required to raise the temperature of the same quantity of water through the same range. Thus, by definition, the specific heat of water is unity.

From the definition of a heat unit the specific heat of a substance is equal to the number of B.t.u. required to raise the temperature of 1 lb. of the substance through one deg. F. from 60° F., or alternatively the number of calories required to heat 1 gramme through one deg. C. from 15° C. and it is often defined somewhat loosely in that way. The actual figure will be the same whichever system is used. Although, strictly speaking, a specific heat should always be expressed as a ratio and on a weight basis, it is often convenient, for combustion calculations, to state the specific heat of a gas on a volume basis and that method is used in this book. For this purpose the specific heat of a gas is expressed as the quantity of heat required to raise the temperature of one cubic foot of the gas measured at some specified temperature and pressure, through one deg. F., or, in the metric system, the quantity required to raise 1 cubic metre through one deg. C.

The figures by the two methods are different and it is also necessary, when quoting a specific heat on a volume basis, to state the temperature and pressure of the gas.

Thus, whilst in the case of water:

$$\text{weight (lb.)} \times \text{temperature rise (deg. F.)} = \text{B.t.u.,}$$

for all other materials:

$$\text{weight (lb.)} \times \text{sp. ht. of material} \times \text{temp. rise (deg. F.)} = \text{B.t.u.}$$

For gases, when considering volumes, the corresponding calculation is:

$$\text{volume (cu. ft.)} \times \text{sp. ht. on volume basis} \times \text{temp. rise (deg. F.)}$$

and the result is given in B.t.u.

The specific heat of a substance is not the same at all temperatures, being in general higher at high temperatures than at low temperatures. Table 1 gives the specific heats of a number of common substances, the values being the mean (i.e. average) for the temperature range shown.

TABLE 1
MEAN SPECIFIC HEATS ON A WEIGHT BASIS

Substance	Specific heat	Over the temperature range	
		° F.	° C.
Water	1.00	60-61	15.6-16.1
Aluminium	0.226	32-212	0-100
Copper	0.102	32-600	0-315
Iron	0.218	32-750	0-399
Firebrick	0.26	32-1,832	0-1,000
Coal	0.25	32-300	0-149
Coke	0.26	70-750	21-399
Steam (at constant pressure)	0.48	212-600	100-315
Air (at constant pressure)	0.243	32-572	0-300
Flue gases of average composition, dry (at constant pressure)	0.24	212-600	100-315

All gases have two specific heats, dependent upon whether they are being heated or cooled while keeping (a) the pressure, or (b) the volume, constant. Heating at constant pressure is far commoner than heating at constant volume; specific heats at constant volume are not generally needed in boiler and furnace combustion practice and are not discussed here. Table 2 gives the specific heats of some common gases.

TABLE 2.
SPECIFIC HEATS OF GASES ON A VOLUME BASIS:

Temperature range	60° F.	0° C.	32-572° F.	0-300° C.
Gas	Specific Heat		Mean Specific Heat	
	B.t.u. per cu. ft. per deg. F. for gas measured at 60° F. and 30 in. Hg.	Kg. cal. per cu. m. per deg. C. for gas measured at 0° C. and 760 mm. Hg.	B.t.u. per cu. ft. per deg. F. for gas measured at 60° F. and 30 in. Hg.	Kg. cal. per cu. m. per deg. C. for gas measured at 0° C. and 760 mm. Hg.
Air	0.0184	0.310	0.0187	0.315
CO ₂	0.0232	0.384	0.0266	0.449
CO	0.0184	0.311	0.0187	0.315
H ₂	0.0182	0.306	0.0184	0.311
CH ₄	0.0217	0.355	0.0269	0.454
O ₂	0.0185	0.312	0.0192	0.324
N ₂	0.0184	0.311	0.0186	0.314
Water vapour	0.0216	0.356	0.0217	0.367
Mixed products of combustion (typical values):				
Temperature range				
0° C.			0.0193	0.326
0-300° C.			0.0202	0.341
0-1,000° C.			0.0222	0.374
0-1,500° C.			0.0232	0.392

To illustrate the use of specific heat, suppose we wish to know how much heat is required to raise the temperature of 1 cwt. of brickwork from 60° F. to 1,780° F.

$$\begin{aligned} \text{Heat required} &= 112 \times (1,780-60) \times 0.26 \\ &\quad (\text{lb.}) \quad (\text{temp. rise}) \quad (\text{sp. ht.}) \\ &= 50,100 \text{ B.t.u.} \end{aligned}$$

Similarly, to calculate how much heat would be released if 750 cubic feet of products of combustion (measured at 60° F. and 30 inches pressure) were cooled from 300° F. to 220° F., the figures would be:

$$\begin{aligned} 750 \times (300-220) \times 0.0201 &= 1,206 \text{ B.t.u.} \\ (\text{cu. ft.}) \quad (\text{temp. rise}) \quad (\text{sp. ht.}) \end{aligned}$$

In accurate work it is necessary to take account of the variation of specific heats with temperature and to use the mean specific heats between the temperatures involved. Thus it may be necessary to calculate the heat above 60° F. remaining in 200 cubic feet of flue gases—measured at 60° F. and 30 inches—(a) at 575° F. (301° C.) and (b) 1,835° F. (1,002° C.). The volume of flue gas obtained from the combustion of 1 lb. of coal under good conditions in a boiler plant is approximately 200 cubic feet measured at 60° F.

(a) Gases at 575° F.

$$\begin{aligned} \text{Heat content} &= 200 \times (575-60) \times 0.0204 \\ &= 2,101 \text{ B.t.u.} \end{aligned}$$

(b) Gases at 1,835° F.

$$\begin{aligned} \text{Heat content} &= 200 \times (1,835-60) \times 0.0223 \\ &= 7,917 \text{ B.t.u.} \end{aligned}$$

The heat content calculated in this way is known as *sensible heat* because any change in heat content is made apparent or can be “sensed” by a change in temperature. This is not so with “latent” heat, which is defined below.

LATENT HEAT

When a substance changes its state, e.g. when water is converted into steam or into ice, it either absorbs or gives up heat, according to the direction of the change, without any change in temperature. As this heat transfer is not shown by a thermometer it is known as "latent" (i.e. hidden) heat of vaporization or fusion. It may be defined as the number of heat units absorbed or released by unit weight of the substance during the change of physical state and may be expressed in B.t.u. per lb. or cal. per gm.

The subject of latent heat, of great importance in steam raising, is referred to again below (Hydrogen and the Latent Heat of Steam) and is dealt with in detail in Chapter 17, where it is shown that the latent heat of steam depends very much upon the pressure (and therefore the temperature) at which the steam is generated or condensed. Latent heat also affects the amount of heat that can be utilized in hot products of combustion containing steam or water vapour.

CALORIFIC VALUE

When a combustible material is burned, heat is developed, the quantity of heat being proportional to the weight of the material burned. The amount of heat liberated per unit weight is not the same for all substances, nor is the heat developed by burning a compound the same as that which would be obtained by burning its constituent elements separately.

The calorific value of any substance is a measure of the heat that can be obtained by burning it, and may be defined as the heat made available when unit weight is burned completely and the products of combustion cooled down to the standard temperature of 60° F. or 15° C. It can thus be expressed as B.t.u. per lb. or cal. per g., the latter units being 1.8 times the size of the former, i.e. calorific value (C.V.) in B.t.u. per lb. $\times 1.8 =$ C.V. in cal. per g. (see Chapter 30).

The calorific value of a gas is defined as the number of heat units liberated by the complete combustion in air of unit volume of the gas, saturated with water vapour, after the products of combustion have been cooled down to 60° F.

In theory the whole of the calorific value of a fuel can be profitably used, e.g. for steam raising, but in practice some of it is always lost by radiation, or as heat carried away by the chimney gases, etc. If the fuel contains hydrogen, and as a result steam is present in the flue gases, it can be argued that this steam does not condense in industrial plant and that consequently the latent heat in it should not be included in the calorific value of the fuel. (See again under "Hydrogen and the Latent Heat of Steam", below.)

Accordingly two calorific values can be quoted for a fuel:

- (1) the "gross" or "higher" calorific value as defined above, including the heat given up by the condensation of any water present in the products of combustion,
- (2) the "net" or "lower" calorific value, obtained by deducting from the gross calorific value the latent heat given up by the condensation and cooling of any water present in the products of combustion (including water previously present as moisture in the fuel).

For this purpose the latent heat of steam, i.e. the latent heat at 60°F., is generally taken as 1055 B.t.u. per lb.

Thus, for solid fuels "Net" C.V. = "Gross" C.V. — 1055 M

where M = weight of moisture present in the products of combustion of 1 lb. of fuel.

Similarly, for a gas,

Net C.V. = Gross C.V. - 50 V

where V = the volume of hydrogen in 1 cu. ft. of saturated gas at 30 in. Hg and 60° F. (measured as a fraction of a cubic foot).

It will be realised that the use of the net C.V. in calculating the efficiency of, for example, a steam boiler will give a higher figure *for the same actual performance* than if the gross C.V. is used. Moreover, if a fuel has a high hydrogen content the efficiency determined on the gross calorific value will be low compared with that of a fuel with a low hydrogen content, even though heat transfer and operational skill are equally good with both fuels. Reckoned on the net calorific value the figures would be more nearly equal.

For these and similar reasons, many engineers have, until recently, used the net calorific value and not the gross calorific value in boiler trial and similar calculations. The present tendency is to use the gross calorific value for all scientific work and for most commercial work. When figures for thermal efficiency are given, it should always be stated whether they are based on a gross or a net calorific value.

The calorific values of some typical solid and liquid fuels are given in Table 3; those of some typical gaseous fuels have been given in Chapter 3.

TABLE 3
CALORIFIC VALUES OF SOME TYPICAL SOLID AND LIQUID FUELS

	Fuel	Gross calorific value of good commercial fuel B.t.u. per lb.	Net calorific value of good commercial fuel B.t.u. per lb.
	N.C.B. classification* code No. of coal		
Coal ..	902	11,100	10,500
" ..	300	14,400	13,900
" ..	206	15,000	14,500
" ..	100a	14,900	14,600
Coke 1% V.M.; 7% ash; 2% moisture		13,200	13,100
C.T.F. 250		16,000	15,400
Fuel oil (C: 86%; H: 12%) ..		18,900	17,800

*The code numbers given are applicable, respectively, to the four coals listed in Table 5, Chapter 6.

Methods used in the laboratory for the direct determination of the calorific value of solids, liquids and gases are described in Chapter 30. The calorific value of a mixture of gases—such as coal gas or producer gas—can be calculated from the volume and known C.V. of the constituent gases; but for accurate work the calorific value of the solid fuels used in a trial should always be determined experimentally on a representative sample of the fuel actually used (see Chapter 29, Sampling).

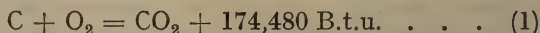
Formulae for calculating the calorific value of a fuel from analytical figures should be used with caution, and only when an experimental figure is not available. One formula for solid and liquid fuels states that

Gross C.V. (B.t.u./lb.) = [14,450 C + 61,500 (H - O/8) + 4,000 S] ÷ 100, C, H, O and S being the respective percentages of carbon, hydrogen, oxygen and sulphur in the fuel.

This formula is stated to give the calorific value of a coal to within about 200 B.t.u. per lb. of the real value.

THERMOCHEMICAL EQUATIONS

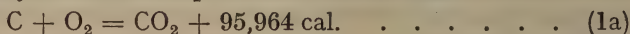
The object of combustion is to produce heat. For this purpose when a fuel is burned it is for the purpose of using the heat resulting from the chemical reactions. Most chemical reactions involved in the use of fuels are *exothermic*; i.e., heat is evolved when they take place. The reaction $C + O_2 = CO_2$ is exothermic, and the fact is commonly represented by what is known as a *thermochemical equation*, thus:



This is interpreted as follows:

When 12 lb. of carbon burn they use up 32 lb. of oxygen, to produce 44 lb. of CO_2 , 174,480 B.t.u. being evolved in the process.

It would be equally correct to express the reaction thus:



This would be interpreted as follows: when 12 grammes of carbon burn, they combine with 32 grammes of oxygen, producing 44 grammes of carbon dioxide; in the process, 95,964 calories are evolved.

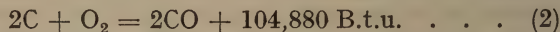
The convention followed is that if the atomic and molecular weights of the substances, expressed in units such as the lb. or the gramme, are the actual weights involved, the amount of heat liberated is the number of British thermal units, or calories indicated as the case may be.

The atomic weight of carbon is 12 and the molecular weights of oxygen (O_2) and carbon dioxide (CO_2) are 32 and 44 respectively. 12 lb. of carbon is termed the *pound-atomic weight* of carbon, 12 grammes being *gramme-atomic weight*. Similarly, 44 lb. and 44 grammes of CO_2 are the *pound-molecular weight* (lb. mol.) and the *gramme-molecular weight*. It will be seen later that these quantities are of special importance when considering the combustion of gases.

If, in a chemical action, 2 or 3 or more atoms or molecules of any substance are involved, the fact is shown in the equation by the appropriate figure 2, 3 etc. preceding the formula. In the resulting calculations the atomic weight or molecular weight must, of course, be multiplied by that figure (2, 3 etc.).

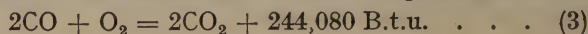
It also follows that if, in order to induce a chemical process to occur, heat has to be applied or put into the system—that is to say, if the chemical reaction is an *endothermic* one—the equation is written similarly to the one given above, but the amount of heat involved is preceded by a *minus* sign.

Equations 1 and 1a represent the overall thermal effect of the ordinary process of burning carbon (e.g. as coke) completely. If the process is an incomplete one, instead of CO_2 being produced, carbon monoxide (CO) will be formed. That is what occurs when there is not enough air for complete combustion. If all the carbon is used up in forming CO, the reaction is represented thus:—



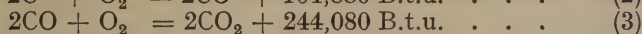
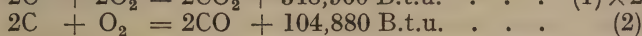
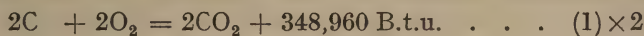
This means that 24 lb. of carbon combine with 32 lb. of oxygen to produce 56 lb. of carbon monoxide and 104,880 B.t.u. are evolved. Comparing this with equation 1 (multiplied throughout by 2, to put it on the same basis as equation 2) we see that when 24 lb. of carbon are completely burnt (to CO_2) we get 348,960 B.t.u. whereas with incomplete combustion we get only 104,880 B.t.u. Thus, the production of CO during combustion represents the liberation of 30 per cent. of the heat obtainable from the carbon if burnt completely (to CO_2).

If we now burn the carbon monoxide, the reaction is represented as follows:



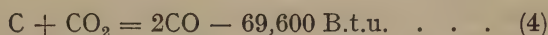
This means that when 56 lb. of CO are burned to form CO_2 , 244,080 B.t.u. are evolved. This represents the balance of 70 per cent. of the heat that incomplete combustion failed to provide.

It should be apparent that if we burn carbon incompletely to form CO only, and then burn the CO thus produced, to form CO_2 , thus obtaining two quotas of heat, the final result is the same as that obtained by burning the carbon completely, to form CO_2 in one stage. This may be seen by tabulating Equations 1, 2 and 3 thus:



It will thus be seen that by adding Equations 2 and 3 we obtain Equation 1 (multiplied by 2 throughout).

It has been stated above that if in order to induce a chemical reaction to proceed, heat has to be put into the system, the reaction is said to be an endothermic one and the thermochemical equation representing it is written thus:—



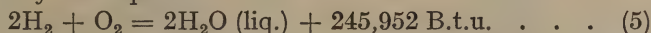
This is the equation representing the action of carbon dioxide on red-hot coke, as in a gas producer.

Thermochemical equations for the action of carbon on steam are given in Chapter 3 (Equations 1 and 2).

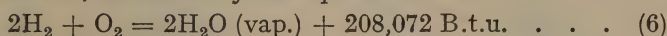
Hydrogen, and the Latent Heat of Steam.

When referring to calorific values, the need was expressed to consider the influence of water formed, from the hydrogen in a fuel, during combustion. The heat available in practice from the combustion of this hydrogen depends upon whether the water formed remains as a vapour (e.g. as steam) or condenses to form liquid water.

If the water vapour condenses within the system the total available heat will be as shown by the equation

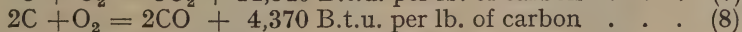
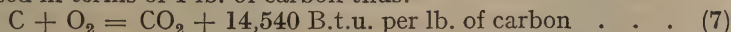


If, however, the vapour passes out of the system without condensing, the net amount of heat available is less by the amount of the Latent Heat of vaporization of water, as shown by the equation

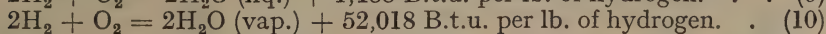
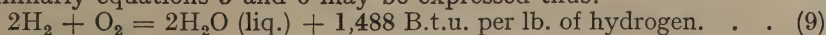


The difference, 37,870 B.t.u., corresponds to 1,052 B.t.u. per lb. of water condensed. That amount (commonly rounded off to 1,055 B.t.u. 1lb.) is the latent heat of water^{1,2} condensing and cooling to 60°F.

Equations 1 and 2, for the formation of CO_2 and CO from carbon, may also be expressed in terms of 1 lb. of carbon thus:



Similarly equations 5 and 6 may be expressed thus:

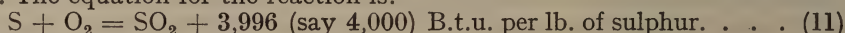


Thermal Loss through Incomplete Combustion.

It follows from Equations 1 and 2 that if instead of the carbon being burned to form CO_2 it is incompletely burned, to form CO, and if the CO is allowed to leave the system unburned, there will be a loss of 10,170 B.t.u. *for every lb. of carbon involved*. This represents 70 per cent. of the potential heat of the carbon (10,170 B.t.u. out of the total of approximately 14,540 B.t.u.)

Sulphur.

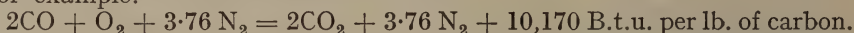
When sulphur is present in a fuel the heat of reaction due to the sulphur forming sulphur dioxide can be included as part of the total heat to be accounted for. The equation for the reaction is:



Nitrogen in the Air.

It is important to remember that when air is used for combustion, instead of oxygen alone (as shown in these equations), the appropriate term for the nitrogen in the air can be added to each side of the equation without affecting the term showing the total heat developed.

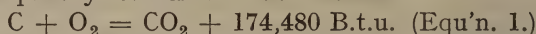
For example:



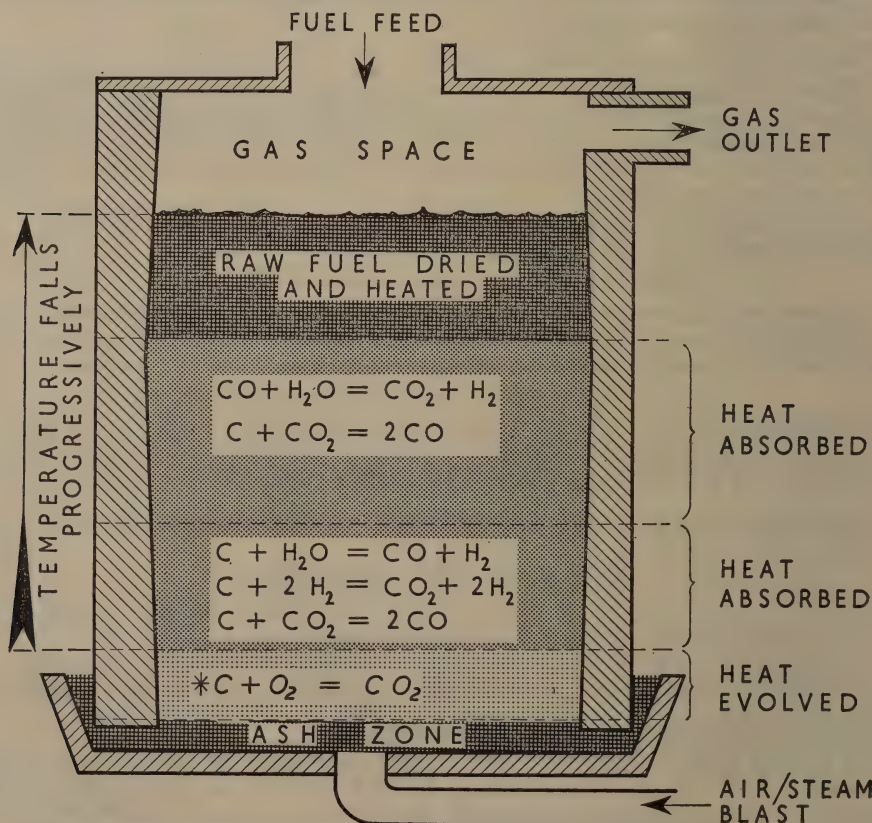
The nitrogen takes no part in the reaction being merely as a rule an unwanted constituent carrying valuable heat away.

GAS PRODUCER REACTIONS

Certain of the reactions that take place in a gas producer are endothermic, as shown in Fig. 1; consequently the exothermic reaction



which occurs in the base of the plant must generate nearly all the heat required to balance the endothermic reaction as well as to compensate for all heat losses,



*Reaction shown in italics is exothermic. All other reactions are endothermic.

FIG. 1. Thermal effects in a gas producer.

including the sensible heat of the gas leaving the producer.

The amount of heat to be supplied by the exothermic reaction can be reduced by adding external heat, e.g. by pre-heating the blast, but in normal practice only a small proportion of the total heat required can be supplied in this way.

Since most of the reactions involving steam in a producer are endothermic and the main exothermic reactions are those using oxygen, the need for a thermal balance between the two types of reaction limits the steam/air ratio in the blast. This in its turn limits the percentage of hydrogen in the gas produced and hence the calorific value of the gas produced. These aspects are referred to again in Chapter 18.

Calorific Value of Carbon.

There are several forms of carbon, including diamond and graphite, each having its own calorific value. In Equation 1 the amount of heat liberated is shown as 174,480 B.t.u. This is on the basis of the calorific value of carbon being 14,540 B.t.u./lb. (8080 cal./gm.), that of carbon as it occurs in metallurgical coke. Much research has been devoted to this subject, with regard to high-carbon fuels and Table 4 gives some of the results.

TABLE 4. CALORIFIC VALUES OF DIFFERENT FORMS OF CARBON

	<i>B.t.u./lb.</i>	<i>cal./gm.</i>
Graphite	14,108	7759
Carbon in metallurgical coke	14,540	8080
Carbon in horizontal retort coke	14,290	7940
Carbon in vertical retort coke	14,380	7990

The fact that different calorific values for carbon are favoured by different workers in this field does not affect the calorific value of carbon monoxide, as expressed in Equation 3.

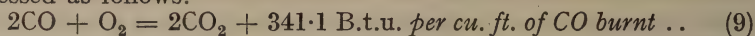
Volumes of Gases.

Although the same principles apply to the combustion of gases as to other fuels, instead of working with weights of fuel, volumes are generally used. It has been experimentally proved that the gramme-molecular weight of a gas, such as CO or CO₂ occupy 22·4 litres at 0°C. and 760 m.m. Hg. The lb.-mol. of a gas occupies, at 32° F. and 14·7 lb./sq. in. abs., 358·7 cu. ft. The volume, of course, depends upon the temperature and/or pressure at which the measurement is made. Other figures given below may be assumed to be those relating to 32° F. and 14·7 lb./sq. in. abs. The volume at 60° F. and 30 in. Hg pressure is 379 cu. ft. (See Chapter 6.)

It is convenient to remember that the ounce-molecular weight of a gas occupies 22·4 cu.ft. and that a cu. ft. of any gaseous carbon compound contains 0·54 oz. of carbon per atom of carbon in its molecule.

Consequently from Equation 1, when 12 lb. of carbon are burned, 358·7 cu. ft. of oxygen are used up and the same volume of CO₂ is produced. The volumes involved at higher temperatures can, of course, be calculated from the gas laws. These statements are valid, strictly speaking, only in respect of perfect gases.

Considering now Equation 3, it can be shown that the reaction can be expressed as follows:



It will be apparent that since volumes of gases represent molecular proportions, for all practical purposes "molecules equal volumes". The result is that many calculations concerning gases used as fuels are relatively simple.

Calorific Value of Gases.

The calorific value of gases are expressed on a volume basis, e.g. B.t.u./cu. ft. It is necessary, of course, to prescribe the temperature and pressure prevailing. In British practice the gross C.V. of a fuel gas is expressed as B.t.u./cu. ft. when the products of combustion are cooled to 60° F. (See B.S.1179.)

The calorific values of some gaseous fuels are given in Table 1, Chapter 3.

EXCESS AIR

Complete combustion cannot be attained in practice unless more than the amount of air theoretically required is used. The necessity for extra air is due to the difficulty of obtaining intimate contact between the air and the combustible gases or finely divided particles, e.g. the fuel itself in the case of a gaseous fuel, or the combustible gases, vapours, and solids leaving the fuel bed when burning solid fuel on a grate. It is also partly due to the need to complete the combustion within the combustion space. Since the concentration of oxygen and of combustibles decreases towards the end of the combustion zone and the speed of a chemical reaction is proportional to the concentration of the reactants, it is necessary to use an excess of oxygen in order to speed up the reaction and complete it before the gases leave the furnace.

For maximum efficiency it is essential that the correct percentage of *excess air*—i.e. the proportion in excess of that theoretically necessary—should be used. If too much is used fuel will be wasted because the extra air will become heated; additional heat will thus pass out of the system as sensible heat in the chimney gases. If too little is used combustion will not be complete and the chimney gases will carry away unused *potential* heat in the form of unburnt combustible gases, such as carbon monoxide, hydrogen and methane, which might have been usefully burnt in the combustion chamber.

The correct or desirable ("optimum") percentage of excess air will depend upon the type of fuel used, the construction of the plant and operating conditions. When burning coal it is usually of the order of 30 to 50 per cent. of the theoretical amount.

Further information on this subject is given in Chapters 6, 8 and 10.

CALCULATION OF EXCESS AIR FROM FLUE GAS ANALYSES

In Chapter 6 a method is given for calculating the composition of the products of combustion when a fuel of known analysis is burned with the amount of air theoretically required for combustion, and the effect of adding excess air is indicated.

In practice it is often necessary when examining the performance of a plant to work in the reverse direction: i.e. to calculate the percentage of excess air from the composition of the flue gases and the analysis of the fuel.

This is usually done by means of a Carbon Balance, i.e. by equating the measured weight of carbon taking part in the combustion process with that reappearing in the products of combustion. As an example let us assume that the fuel used for the calculations in Chapter 6, page 102 is burned in a boiler and that the flue gases have the following composition by volume:

Constituent ..	CO ₂	CO	H ₂	O ₂	N ₂
Per cent.	11.73	0.20	0.09	6.81	81.17

It will be observed that no figure is given for SO₂. Actually the flue gases will contain some SO₂, which will be recorded as CO₂, but the error thereby involved is small.

Let us assume also that analysis of the clinker and of the ash shows that 1 per cent. of the fuel is removed by them from the system as unburnt carbon.

The weight of carbon in 1 lb. of dry flue gas can be calculated from the flue gas analysis (which, as in normal practice, is given by volume on a dry basis) using Table 5.

TABLE 5

1	2	3	4	5
<i>Flue gas constituent</i>	<i>Per cent. by volume</i>	<i>Proportion by weight</i>	<i>Per cent. by weight</i>	<i>Weight of carbon per lb. dry flue gas</i>
CO ₂	11.73	$0.1173 \times 0.1163 = 0.01364$	17.05	lb. 0.04653
CO	0.20	$0.0020 \times 0.07400 = 0.00015$	0.19	0.00081
H ₂	0.09	$0.0009 \times 0.00533 = 0.000005$	0.01	..
O ₂	6.81	$0.0681 \times 0.08457 = 0.00576$	7.20	..
N ₂	81.17	$0.8117 \times 0.07446 = 0.06044$	75.55	..
		Total weight = 0.07999		
	100.00	Total weight of carbon ..	100.00	0.04734

The proportion by weight (column 3) is found by multiplying the items of column 2 by the appropriate weight per cubic foot (Table 3, Chapter 6). Column 5 is compiled by multiplying the items of column 4 by the proportion of carbon in each gas, making use of the atomic weights of the elements comprising the gas (Table 1, Chapter 6).

The method of calculating the weight of carbon per lb. of dry flue gas using the mol technique, referred to in Chapter 6, will now be shown. The analysis of the flue gas by volume and the number of mols of each constituent in 100 mols of flue gas will each be the same, owing to the equivalence between mols and volumes for gases. The weight in pounds of each constituent in 100 mols of flue gas will then be obtained by multiplying the number of mols of the constituent by its molecular weight. (See Table 6.)

TABLE 6

<i>Flue gas constituent</i>	<i>Mols per 100 mols of flue gas</i>	<i>Weight per 100 mols of flue gas</i>	<i>Per cent. by weight</i>	<i>Weight of carbon per lb. dry flue gas</i>
		lb.		lb.
CO ₂	11.73	$44 \times 11.73 = 516.1$	17.13	0.04672
CO	0.20	$28 \times 0.20 = 5.6$	0.19	0.00081
H ₂	0.09	$2 \times 0.09 = 0.2$	0.01	..
O ₂	6.81	$32 \times 6.81 = 217.9$	7.23	..
N ₂	81.17	$28 \times 81.17 = 2,273$	75.44	..
		Total weight = 3,012.8		
		Total weight of carbon ..		0.04753

From the fuel analysis the weight of carbon in 1 lb. of fuel (as fired) is 0.740 lb. Deducting the weight of carbon in the clinker and ash (0.010 lb.) we get the weight of carbon in 1 lb. of fuel entering into combustion and appearing in the flue gases. Hence the weight of dry flue gas corresponding to 0.730 lb. of C. (or 1 lb. of fuel) = $\frac{0.730}{0.04734} = 15.42$ lb.

To obtain the weight of wet flue gas it is necessary to add the weight of moisture present. This is (a) the moisture in the fuel *plus* (b) the moisture produced by the combustion of hydrogen in the fuel. The hydrogen entering into combustion is the hydrogen in the fuel *minus* the unburnt hydrogen in the flue gas. From the last table the hydrogen in the flue gas is 0.01 per cent. by weight of the dry gas, corresponding to 0.0001×15.4 i.e. 0.00154 lb. per lb. of fuel. Hence the weight of hydrogen entering into combustion is

$$0.050 - 0.00154 = 0.0485 \text{ lb.}$$

and this will produce 0.0485×8.937 , i.e. 0.433 lb. of moisture.

The total *weight of wet flue gas* is, therefore

$$\begin{array}{rcc} 15.42 & + & 0.433 & + & 0.09 \\ \text{(dry} & & \text{(moisture from} & & \text{(moisture} \\ \text{flue gas)} & & \text{combustion)} & & \text{in fuel)} \\ & & \text{i.e. } 15.94 \text{ lb. per lb. of fuel.} \end{array}$$

The weight of fuel becoming gasified

$$\begin{aligned} &= 1 - (\text{ash} + \text{carbon in ash}) = 1 - (0.05 + 0.01) \\ &\text{i.e. } 0.94 \text{ lb. per lb. of fuel fired.} \end{aligned}$$

Hence *weight of air* used (which equals gross weight of wet flue gas *minus* the weight of fuel gasified in combustion)

$$= 15.94 - 0.94, \text{ i.e. } 15.0 \text{ lb. per lb. of fuel.}$$

But from page 100 (Chapter 6) the air theoretically required is only 10.0 lb. per lb. of fuel.

Therefore amount of excess air = 50.0 per cent.

CALCULATION OF HEAT LOSSES FROM SOLID FUELS

When fuel is burned in a boiler furnace part of the heat developed will be usefully employed in raising steam, but the remainder will leave the system in various ways, and will be wasted. Some of the heat will be lost by radiation, some in the sensible heat of the ashes and clinker, and some in the potential heat in the unburnt carbon in the clinker, but these losses will be small compared with the heat carried away by the flue gases. This latter may be divided into the heat carried away (1) in the excess air, (2) in the dry products of combustion, (3) in the water vapour and (4) as potential heat in unburnt combustible gases.

If the heat losses can be reduced, a larger proportion of the heat in the fuel will be usefully employed: it is, therefore, important to know the heat losses that can be attributed to each of these items and their effect upon efficiency.

They may be calculated in terms of heat lost per lb. of fuel as follows, taking the same fuel and flue gas analyses as before. Let us assume that the exit temperature of the flue gases is 560°F. and the atmospheric temperature is 60°F.

(1) Heat Lost in Excess Air.

The sensible heat carried away in the flue gases by the excess air equals its weight (in lb.) \times the temperature rise (deg. F.) \times mean specific heat of air = $5.0 \times 500 \times 0.243$ i.e. 610 B.t.u. per lb. of fuel.

(2) *Heat Lost in Dry Products of Combustion.*
The sensible heat of the dry flue gas will be as shown in column 6 of Table 7.

TABLE 7

1	2	3	4	5	6
Flue gas constituent	Analysis		Weight per lb. fuel	Volume per lb. fuel	Sensible heat
	Per cent. by volume	Per cent. by weight			
			lb.	cu. ft.	B.t.u.
CO ₂	11.73	17.05	2.629	22.61	$22.62 \times 500 \times .0266 = 301$
CO	0.20	0.19	0.029	0.39	$0.39 \times 500 \times .0187 = 4$
H ₂	0.09	0.01	0.002	0.4	$0.4 \times 500 \times .0184 = 4$
O ₂	6.81	7.20	1.11	13.1	$13.1 \times 500 \times .0192 = 126$
N ₂	81.17	75.55	11.65	156.5	$156.5 \times 500 \times .0186 = 1,455$
Total volume 193.0					Total heat loss .. = 1,890

Columns 2 and 3 are taken from the preceding table.
Column 4 is obtained by multiplying the items of column 3 by the number of pounds of dry gas per lb. of fuel and dividing by 100.
Column 5 consists of the items in column 4 divided by the appropriate weights in lb. per cu. ft. (See Table 3, Chapter 6.)
Column 6 is obtained by multiplying the items of column 5 by the number of degrees of temperature rise (560–60) and the mean specific heat for that temperature rise calculated from information given in Table 2.
The heat lost in the dry products of combustion is equal to the heat lost in the dry gas *minus* the heat lost in the excess air.
Hence heat lost in dry products of combustion
= 1,890 – 610 i.e. 1,280 B.t.u. per lb. of fuel.

(3) *Heat Lost in Water Vapour.*
This will be the total heat of the water vapour in the flue gases at its partial pressure and temperature in the flue gases *minus* its heat content as water at room temperature and pressure.
The partial pressure of the moisture will be
$$\text{atmospheric pressure} \times \frac{\text{volume of the moisture at } 60^{\circ} \text{ F. and } 30 \text{ in. Hg.}}{\text{volume of the flue gases at } 60^{\circ} \text{ F. and } 30 \text{ in. Hg.}}$$

The volume of the moisture at 60° F. and 30 in. Hg.
= (0.433 + 0.09) lb. × 21.00 i.e. 11.0 cu. ft. per lb.
The volume of the dry gases = 193.0 cu. ft. (column 5 preceding Table)
Hence the partial pressure = $14.7 \times \frac{11.0}{193.0 + 11.0}$
i.e. 0.793 lb./sq. in. absolute.
From the Steam Tables the total heat of superheated steam at 0.795 lb./sq.in. and 560° F=1,317 B.t.u. per lb.
Therefore (a) heat lost in moisture evaporated from fuel
= 0.090 × [1,317 – (60 – 32)] i.e. 116 B.t.u.

and (b) heat lost in moisture formed during combustion

$$= 0.433 \times 1,289 = 558 \text{ B.t.u.}$$

Total heat carried away by moisture = 674 B.t.u. per lb. of fuel.

(4) *Heat Lost in Combustible Gases.*

The potential heat lost in combustible gases will be equal to the volume of each constituent multiplied by its calorific value at 60° F. and 30 in. Hg.

The gross calorific values of the principal combustible flue gas constituents, measured at 60° F. and 30 in. Hg and on a dry basis, are:

CO — 341.1 B.t.u. per cu. ft.

H₂ — 343.2 B.t.u. per cu. ft.

CH₄ — 1,067.2 B.t.u. per cu. ft.

Hence, in the example given,

$$\begin{aligned} \text{Heat lost in CO} &= 0.39 \text{ (cu. ft.)} \times 341.1 \text{ (C.V.)} \\ &= 133.2 \text{ B.t.u.} \end{aligned}$$

$$\begin{aligned} \text{Heat lost by hydrogen} &= 0.4 \times 343.2 \\ &= 137.3 \text{ B.t.u.} \end{aligned}$$

$$\text{Total} = 270.5 \text{ B.t.u. per lb. of fuel.}$$

(5) *Heat Lost in Combustible Solids.*

It may be assumed that the combustible matter in the clinker and ash has a calorific value of 14,500 B.t.u. per lb. The amount present is 0.010 lb. per lb. of fuel.

$$\text{Hence the potential heat lost} = 0.010 \times 14,500$$

$$\text{i.e. } 140 \text{ B.t.u. per lb. of fuel}$$

(6) *Sensible Heat in Clinker and Ashes.*

The temperature of the clinker and ashes leaving the system will depend on the method of firing. Assume that for hand-firing this temperature is 1,000° F.

If we assume all the ash in the fuel is removed in this way the heat lost will be weight \times specified heat \times temperature rise (from 60° F. to 1,000° F.).

$$= 0.05 \times 0.165 \times 940 = 8 \text{ B.t.u. per lb. of fuel.}$$

HEAT ACCOUNT, HEAT BALANCE

As all the heat in the fuel must either be given to the steam or appear in the losses it is possible to construct a heat account or balance sheet showing how every heat unit has been accounted for. The heat account for the case just considered could take the form shown in the example given below.

For the purposes of this example the calorific value of the fuel has been calculated from the chemical composition. It is assumed that the heat given to the steam, when calculated according to the methods given in Chapter 26, is 1,253 B.t.u. per lb. and that the evaporation, determined in a boiler trial, is 7.68 lb. of water per lb. of fuel.

Item in heat account	Heat per lb. fuel B.t.u.	Per cent.
Heat in fuel (gross calorific value)	13,390	100.0
Heat obtained in steam (boiler efficiency)	9,623	71.9
Heat lost in flue gas:		
in excess air	610	4.6
in dry products	1,280	9.6
in moisture in fuel	116	0.9
in moisture from combustion	558	4.2
in combustible gases	271	2.0
Heat lost in combustible solids	140	0.1
Heat lost in clinker and ash	8	1.5
Balance of heat account (Radiation and unaccounted for)	784	5.7

RADIATION

It will be noted that the residue or balance of the heat account is described as "Radiation and Unaccounted for". In some scientific investigations radiation losses are calculated from direct measurement of the temperature of the wall of the setting, but it is more usual to take it as the difference between the heat supplied and the sum of the ascertained or accurately measured losses.

It will be realised that the figure so obtained includes any other unmeasured losses and is affected appreciably by any errors made in calculating other items. The figures obtained for radiation in repeat (replicate) trials, therefore, provide a check on accuracy. In commercial trials the variation between two trials made under similar conditions should not exceed $\pm 2\%$, and in scientific trials it should be less.

GRAPHICAL METHODS

In order to save laborious calculations many charts, diagrams and nomograms have been published showing the percentage of excess air and the heat losses occurring at different temperatures when the flue gases from coal, oil, gas and other fuels contain specified percentages of CO_2 . Usually, but not always, they assume that no combustible gases are present in the flue gases, and they apply to only one particular fuel. They do not, for example, allow for the chemical differences between different types of coal. Some caution should therefore be exercised in using them, but they are sufficiently accurate for many purposes and they can frequently be used to give a quick check on operating conditions. Examples can be found in Chapter 26, and in "Technical Data on Fuel"¹.

DEDUCTIONS FROM HEAT ACCOUNT

An examination of the heat account shows that the main heat losses are those due to the sensible heat carried away by the dry products of combustion, the excess air and the moisture in the flue gases. All these losses can be lessened by lowering the temperature of the flue gases; methods of doing this either by installing auxiliary equipment or by more efficient operation of the plant are indicated in other chapters.

The sensible heat losses can also be lessened by reducing the weight of the flue gases. In effect this means reducing the percentage of excess air to the lowest practicable amount by avoiding air infiltration, by ensuring that the air admitted over the fire is intimately mixed with the combustible gases leaving the fuel bed (see Chapter 8) and by reducing it to the minimum required to avoid combustible gases leaving the combustion chambers unburned.

Since dilution of the products of combustion with excess air lowers the percentage of CO_2 in the flue gases, the percentage of CO_2 is a measure of the amount of excess air and, therefore, of the sensible heat lost. Fig. 2 illustrates the marked extent to which variations in CO_2 content and temperature affect sensible heat losses and therefore boiler efficiency.

It will be noted that although in the example given above the flue gases contained only 0.20 per cent. of CO and 0.09 per cent. of H_2 , the loss due to incomplete combustion was 2 per cent. It is possible to have many times this quantity of combustible gases in the flue gas, in which case the heat loss is correspondingly increased to an extent not always realised by boiler users.

In a series of trials carried out on a hand-fired Lancashire boiler it was found that the optimum amount of excess air was 34 per cent. *Increasing* the excess air to 120 per cent. reduced the efficiency from 72 per cent. to 60 per cent.

through increased sensible heat losses. *Reducing* the excess air to 15 per cent. caused the same loss by incomplete combustion. (See Fig. 5, Chapter 8.)

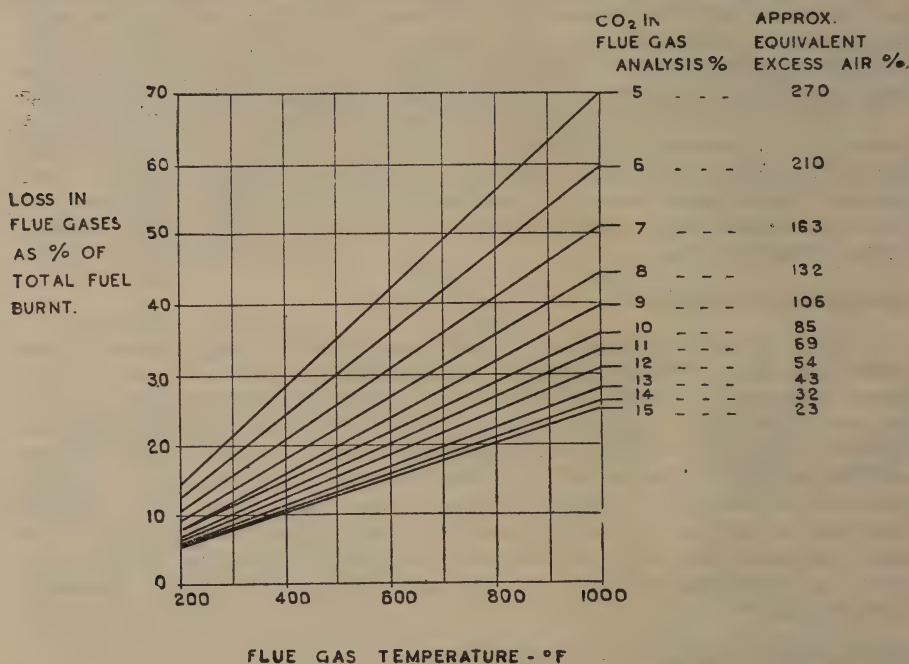


FIG. 2. Effect of temperature and excess air on heat losses.

It is extremely difficult to detect small quantities of combustible gases with the type of apparatus commonly used for flue gas analysis in industrial installations but fortunately with bituminous coal their presence is invariably accompanied by visible smoke emission from the chimney. The practical indications of efficient boiler operation are therefore:

- (1) high CO₂ content,
- (2) low flue gas temperatures,
- (3) little or no smoke.

COMBUSTION OF TOWN GAS

The method of calculating the composition of the products of combustion which would result if town gas could be completely burned with the exact quantity of air theoretically required has been given in Chapter 6. It is just as necessary, however, to use excess air when burning gas as when burning coal, and for similar reasons.

The quantity of air actually used can be calculated from the flue gas analysis by means of a *carbon balance*, following the methods already described in relation to coal, and a heat balance can be constructed using the same technique as for coal. It can also be shown that when burning gas it is just as important to avoid the presence of combustible gases in the flue gases as in the case of coal.

If no combustible gases are present in the flue gas the percentage of excess air can be calculated very simply by the following method. Take as an example the gas selected for the calculations in Chapter 6, from which the products of combustion, per cubic foot of gas, were:

CO ₂	..	..	..	0.508	cu. ft.
H ₂ O	..	..	..	1.228	" "
N ₂	..	..	..	4.018	" "
Total ..				5.754	" "

Then percentage of CO₂ in flue gas

$$= \frac{\text{cu. ft. CO}_2 \text{ produced per cu. ft. of gas} \times 100}{\left\{ \begin{array}{l} \text{cu. ft. of (CO}_2 + \text{N}_2) \text{ produced by combustion} \\ \text{of 1 cu. ft. of gas with theoretical air} \end{array} \right\} + \left\{ \begin{array}{l} \text{cu. ft. of excess air} \\ \text{per cu. ft. of gas} \end{array} \right\}}$$

Therefore in the example, if X is the cu. ft. of excess air per cu. ft. of gas,

$$\text{CO}_2\% = \frac{0.508 \times 100}{0.508 + 4.018 + X}$$

whence $X = \frac{50.8}{\text{CO}_2\%} - 4.526$

IGNITION TEMPERATURE

The lowest temperature in a combustion process at which chemical reaction proceeds under certain specified laboratory conditions without heat being supplied from an external source is termed the "ignition temperature". This temperature does not necessarily correspond with the fuel starting to glow or with the first appearance of flame, as in many circumstances there is an earlier period during which slow combustion takes place.

The subject is an extremely complicated one and the following account gives only the broad essentials. The field is rich in scientific literature, which should be consulted by anyone who wishes to pursue the subject seriously.

No substance will burn until it has been raised to a temperature at which its reaction with oxygen is sufficiently rapid. Visible ignition is preceded by a temperature range in which slow combustion occurs. This is illustrated by the behaviour of coal during storage (Chapter 5).

The ignition temperatures in air of a number of fuels are given in Table 8. These temperatures are not absolute, but depend to a greater or lesser extent on the conditions.

TABLE 8. IGNITION TEMPERATURES IN AIR

	° C.	° F.
Gas coal	370	700
Ordinary bituminous coal	400-425	750-800
Welsh steam coal	470	880
Anthracite	500	930
Coke (soft)	425-500	800-930
Coke (hard)	500-650	930-1,200
Hydrogen	580-590	1,080-1,095
Carbon monoxide	644-658	1,191-1,216
Methane	650-750	1,200-1,380
Ethane	520-630	970-1,170
Ethylene	542-547	1,008-1,016
Benzene	740	1,365
Toluene	810	1,490
Ethyl alcohol	558	1,036
Cylinder oil	417	783
Gas oil	336	633
Kerosene	295	562

IGNITION LIMITS

If only a trace of gas is added to air and the mixture is brought into contact with a flame or an electric spark the mixture will not ignite. If, for example, the mixture consisted of 3 per cent. of coal gas with air there will be no ignition. As the percentage of coal gas is increased ignition occurs only when the limiting value is reached at 5.3 per cent. This is known as the *lower limit of inflammability*. Increasing the proportion of gas renders the mixture more readily ignitable, but as the percentage of gas is still further increased the inflammability becomes less again until from 31 per cent. of gas upwards there is again no ignition. This is known as the *higher limit of inflammability*. The limits of some industrially important gases are given in Table 9.

TABLE 9. LIMITS OF INFLAMMABILITY IN AIR

Substance	Lower limit: per cent. by volume	Higher limit: per cent. by volume
Coal gas	5.3	31
Benzene	1.4	7.5
Blast furnace gas	35.0	74
Carbon monoxide	12.5	74
Hydrogen	4.0	75
Methane	5.0	15

FLAME SPEED AND ITS EFFECT ON INDUSTRIAL BURNERS

When an inflammable mixture of gas and air in a tube is ignited, the resultant flame travels through the mixture, at first with a constant velocity and subsequently under suitable conditions with an accelerating velocity. This occurs particularly in conditions of turbulence. Conditions of deterioration may ultimately be reached in which the flame speed becomes accelerated to a very high velocity of the order of 3,300–6,600 feet per second.

Fig. 3 shows the relation between speed of flame propagation and composition of the mixture of combustible and air for the important constituents of gaseous fuels.

The industrial significance of these properties of flame propagation is that as the composition of a gaseous fuel varies so is there a corresponding change in the tendency for the gas burner to "back-fire".

The burner is said to "back-fire" when the speed of backward propagation of the flame exceeds the velocity of flow of the combustible mixture of gas and air in the burner tube. The high flame speed of hydrogen causes gases rich in hydrogen to tend to back-fire.

There is also a tendency for the burning gases to be blown off the burner head when the forward velocity of the combustible mixture exceeds the speed

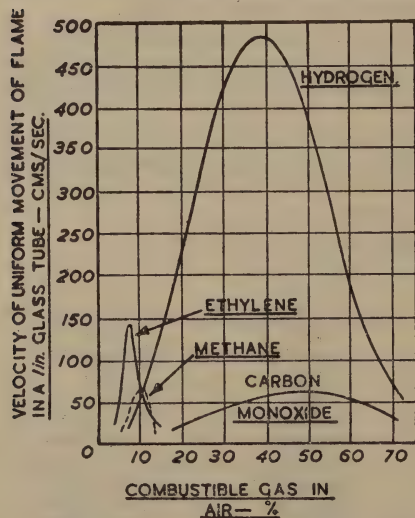


FIG. 3. Speed of flame propagation for various mixtures of air with combustible gases. Summary of Professor Wheeler's results.

(Reproduced by permission of the publishers (Walter King) from "Theory of Industrial Gas Heating", by Peter Lloyd.)²

of flame propagation. The high flame speed of hydrogen assists stability of the burner head.

FLAME TEMPERATURE

The temperature that is attained by a gas flame, and the flame of the volatile matter from coal depend upon the following factors:

(a) *Calorific value of the gas or vapour.*

The heat supplied to the flame is obtained mainly from the combustion of the fuel. Since the steam formed by combustion will leave the flame uncondensed the heat that is available is represented by the net C.V. and not the gross C.V.

(b) *Sensible heat of the air and gas.*

If either the air or the gas is pre-heated the sensible heat thus given to the reacting substances will be added to the heat derived from combustion.

These two items together (*minus* item (e) below), make up the total heat input into the flame.

(c) *Quantity and specific heat of the products of combustion.*

The heat derived from the combustion of the gas is used for heating the products of combustion up to the flame temperature. The mass of the products of combustion multiplied by their total heat capacity over the temperature range represents the heat thus utilized. Since the specific heat of gases varies with the temperature, precise knowledge of the specific heat at high temperatures is required for the determination of the "theoretical flame temperature" so defined.

Clearly the less the heat required by the products of combustion, the higher will be the flame temperature. Inerts in the gas or any gases, added to the flame, which do not take part in the combustion must reduce the flame temperature.

(d) *Excess air.*

Any excess air used in the flame will add heat if the air is pre-heated but will on balance remove heat from the flame since the excess air must itself be raised to flame temperature.

(e) *Dissociation.*

The combustion reactions $C + O_2 = CO_2$ and $2H_2 + O_2 = 2H_2O$ are reversible at high temperatures. Consequently a proportion of the heat of combustion must be subtracted from item (a) according to the extent to which the combustion is incomplete at these higher temperatures. The higher the temperature of the flame the more incomplete will be the combustion in the flame. This effect is usually ignored in practice.

(f) *Radiation from the flame.*

Theoretical flame temperatures are calculated on the assumption that no heat is radiated from the flame. But the purpose of producing a flame is that it shall do work, i.e. that heat *shall* be radiated from it as, in fact, it is. For this reason flame temperatures are always in practice lower than the theoretical flame temperatures calculated according to the factors (a) to (e).

Neglecting the loss of heat from radiation under (f), the theoretical flame temperature is thus given by the expression:

$$\frac{\text{net C.V. of gas} + \text{sensible heat of gas and air} - \text{heat lost by dissociation}}{\text{vol. of products} \times \text{sp. ht. per unit volume at constant pressure}}$$

Calculations of flame temperature made upon these principles, the accuracy of which has been confirmed experimentally, indicate that with the exception of acetylene which is somewhat above the range and with a slight exception for hydrogen and carbon monoxide all gases containing the normal quantity of inerts up to, say, 10 per cent. or so have virtually the same flame temperature.

This is because any additional heat given to the flame by increased calorific value is counter-balanced by a greater quantity of products of combustion.

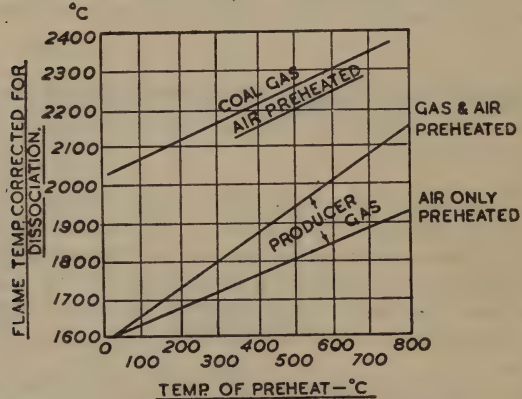
Flame temperature has a special significance as governing the thermal

TABLE 10. FLAME TEMPERATURES OF GASES AND VAPOURS

	<i>Gross C.V. of gas: B.t.u./cu. ft.*</i>	<i>Inerts in gas: per cent.</i>	<i>Flame temperature</i>	
			<i>° F.</i>	<i>° C.</i>
Acetylene	1,500	nil	4,230	2,340
Ethylene	1,560	nil	3,700	2,040
Natural gas	1,220	1	3,645	2,030
" "	1,000	0.5	3,612	1,990
Coal gas "	560	6	3,710	2,045
" " "	475	10	3,710	2,045
Blue water gas ..	295	9	3,780	2,080
Hydrogen	320	nil	3,960	2,180
Carbon monoxide ..	318	nil	3,960	2,180
Producer gas	165	56	3,280	1,800
" " "	128	61	3,050	1,690
Blast furnace gas ..	92	71	2,660	1,460

* at 60° F. and 30 in. Hg. sat'd.

efficiency of the evolution of heat from flames. This is measured by the ratio of temperature difference between the flame temperature (t_1), and that of the issuing flue gases (t_2), i.e. $(t_1 - t_2)/t_1$. See Table 10.



The lower flame temperatures of the last three gases are due to their high content of inerts. The flame temperature can be raised by pre-heating both air and gas as indicated in Fig. 4. This fact also indicates the very considerable influence of excess air in cooling the flames.

FIG. 4. The effect on flame temperature of pre-heating air.
(A. Fells, *Trans. Inst. Gas E.*, 83, 612.)

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CHAPTER 8

COMBUSTION OF SOLID FUELS IN PRACTICE

THIS Chapter deals with the practical aspects of the combustion of solid fuels. The utilization of liquid fuels is dealt with in Chapter 13. Some of the fundamental principles are, of course, applicable to all fuels.

Theoretically, perfect combustion is attained when a fuel is burned with the exact quantity of air required—no more, no less. But in practice, complete combustion is not achieved unless a substantial excess of air is provided.

The fuel and air must be brought into contact under the right conditions, namely:

- (a) an adequate proportion of air *at the right places* throughout the fuel;
- (b) adequate *time* and *turbulence* must be arranged at a *temperature* sufficiently high to ensure that the chemical reactions involved are completed within the available combustion space. (These three factors are sometimes familiarly referred to as “the three Ts.”)

The Air Supply

To bring the air into contact with the fuel and then remove the products of combustion there must be a flow of gases throughout the system, as shown in Fig. 1. Part of the air that has entered the furnace is needed for the combustion reactions, the unwanted excess simply becoming heated. The hot gaseous products of the combustion as well as the excess air pass through the remainder of the system, to which they give up most of their heat.

DRAUGHT

Incomplete and inefficient combustion result in a very serious waste of fuel. The causes include: insufficient air; failure to make proper use of such air as is supplied; irregularity in the fuel bed. The remedy is usually a combination of measures, in which proper arrangements for draught play the predominating part.

Admission of air to the furnace, and the subsequent movement of gases throughout the system are brought about in several ways:

- (a) the air may be drawn in by the natural draught created by the chimney;
- (b) the air may be drawn in by a fan at the chimney base (*induced draught*);
- (c) the air may be forced in under pressure by a fan (*forced draught*), the pressure serving to propel the gases onwards through the fuel bed and the chimney draught being used to remove the gases;
- (d) the air may be forced in through the action of a steam jet in a venturi, the chimney being used as in (c);
- (e) the air may be forced in by a fan, the products of combustion being removed by a second fan, or by chimney action, in such a way as to leave zero pressure in the combustion space above the fuel bed. This system is known as *balanced draught*. This is by far the most flexible arrangement.

Although zero pressure is referred to, in practice a slight suction (partial vacuum), of the order of 0.05 in. w. g., is arranged at the front of the grate to reduce or eliminate the emission of smoke or flame from the fire door and overheating of the furnace front that might be caused by a very slight excess of pressure.

The amount of draught required depends upon (a) the nature of the fuel

(b) the depth of the fire to be maintained, (c) the rate of combustion desired, (d) the design of the boilers and of the flues and (e) the combined resistances of ancillary plant such as economisers, air heaters, regenerators or recuperators, waste-heat boilers and so forth.

Some fuels require more draught than others. With coke, anthracite, and low-volatile coals most of the air for combustion must be drawn through the fuel bed as primary air and this is subject to the resistance of the fuel bed. With high-volatile fuels, a considerable proportion of the combustible material of the fuel is distilled off, passing away without burning, and must therefore be burned with the help of secondary air. Since this is drawn in through openings that offer virtually no resistance to flow, the draught required to burn high-volatile fuel is less than that needed for low-volatile fuel. Furthermore, the fuel bed resistance increases as the size of the fuel decreases, so a coal containing a high proportion of fines requires a stronger draught than a graded coal such as "singles".

The amount of air that can be drawn into a fuel furnace is governed by (a) the cross sectional areas of the flues and the chimney, (b) the draught provided and (c) the combined resistances of dirty flues and other similar obstructions. Since the dimensions in an *existing* plant are generally fixed, only the draught can be varied. The manner of arranging this depends upon the system used.

Natural Draught

The factors concerned in the provision of natural draught are (a) the height of the chimney and (b) the average temperature of the gases within the chimney; the higher the chimney and the hotter the gases, the greater is the resulting draught. Both methods of obtaining draught are expensive (a) owing to capital costs and (b) because in order to create draughts we have to use heat that might be more profitably used to raise steam or to do other useful work. Thus, if the provision of adequate draught necessitates an outlet gas temperature say 100 deg. F. higher than is otherwise necessary, the heat used for this purpose is

$$\begin{matrix} 204 & \times & 0.6202 & \times & 100, & \text{i.e., 410 B.t.u. per lb. of coal burned.} \\ \text{(cu. ft.} & & \text{(sp. ht.} & & \text{(temp.} & \\ \text{of flue} & & \text{of flue} & & \text{rise)} & \\ \text{gas)} & & \text{gas)} & & & \end{matrix}$$

This can be shown to be about 3 per cent. of the total heat of the coal, possibly equivalent also to about 3 per cent. of the total cost of the coal, including the handling charges.

These statements are valid only in very general terms. As already stated, the cross-sectional area of the chimney is very important, because the greater velocity of the gas flow is due to the higher temperature of the gases which, in turn, results in a greater volume of gas. The capacity of a chimney is determined by the weight of flue gases passing in unit time.

It is difficult to prescribe figures and quantities. The following may be taken as fairly representing average practice for a Lancashire boiler.

Chimney height feet	Draught		Combustion rate : lb. of coal per sq. ft. hr.
	at chimney base in.w.g.	at bridge in.w.g.	
100-120	0.65	0.3	20
120-150	0.9	0.4	25
150-200	1.1	0.5	30

Mechanical Draught

Mechanical draught is provided by fans and may, of course, be increased later by providing larger fans, a point that should be kept in mind when planning new boiler installations, ample margin also being necessary to allow for possible overloading of the fans.

The use of *steam jets* requires caution. In ordinary practice not more than about 5 per cent. of the steam output of the boiler should be used for this purpose; this limit is often inadvertently greatly exceeded through failure to realise the extent of erosion and consequent enlargement of the bore of the jet that takes place in the course of time.

The discharge through a small steam jet can be shown to be

$$51A(P + 15) \text{ lb. per hr.}$$

where A = Area of the jet, in sq. in.,

and P = gauge pressure of steam, in lb./sq. in.

Thus a very small amount of wear will cause a very large increase in the area and, in consequence, a large increase in the amount of steam used and, therefore, a serious waste of steam.

Apart from the matter of wear, fine jets operating at high pressure are more economical than large jets operating at low pressure. Table 1, giving figures for steam discharge from jets, has been calculated from this formula.

TABLE 1
STEAM CONSUMPTION OF JETS

Gauge pressure lb./sq. in.	Lb. of sat. steam passed per hour by each jet			
	Diameter			
	$\frac{1}{32}$ in.	$\frac{1}{16}$ in.	$\frac{1}{8}$ in.	$\frac{1}{4}$ in.
10	1	4	16	63
35	2	8	32	126
60	3	12	47	189
85	4	16	63	252

Among the advantages of mechanical draught are—

- Cheaper low-grade fuels can be used, and the rate of evaporation can be increased.
- Efficient combustion is more easily attained and smoke production more easily avoided because of the greater ease of air control.
- Furnace control is simplified.
- Smaller chimneys can be used.
- Heat transmission efficiency can be increased, for example, in the case of high velocity Economic Boilers.

Mechanical draught is further discussed in Chapter 15; in this chapter attention is concentrated on natural draught.

CALCULATION OF NATURAL DRAUGHT

The limitations of the available draught will be clearer from a study of the basic cause of air movement through a furnace and its flues, and thence out to the atmosphere by way of the chimney.

In effect, the chimney, furnace and outer air constitute a gigantic U-tube. The chimney is one vertical limb; the other limb is a hypothetical column of cold air. The furnace or boiler with the interconnecting flues is represented by the lower, horizontal portion of the U-tube, as shown in Fig. 1.

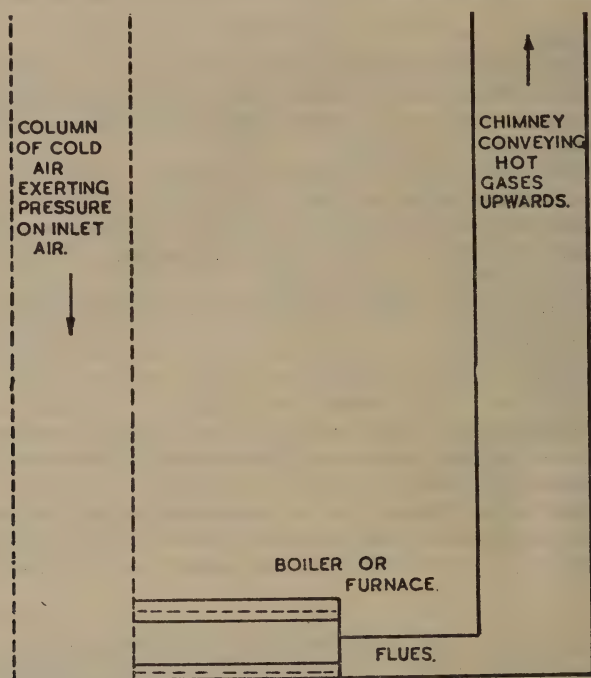


FIG. 1. Natural draught. Similarity between a chimney and a U-tube containing fluids of different densities in the two limbs.

If the chimney is 100 ft. high, the weight of a column of air above 1 sq. ft. of area at 60° F. is 7.6 lb, while that of a column of typical flue gases, also at 60° F., is 7.9 lb. But the weight of any gas just filling the column is inversely proportional to its absolute temperature ($t^{\circ}\text{F} + 460$), so, if the mean temperature of the stack gases is 350° F., the weight of the column of flue gases will be

$$7.9 \times \frac{460 + 60}{460 + 350} \text{ i.e., } 5.1 \text{ lb.}$$

Since the contents of the limb of the U-tube containing air are heavier than those of the other limb, a continuous motion is set up, the heavier atmospheric air descending and the lighter hot flue gases being thus caused to rise. The amount of degree of "unbalance" represents a pressure of:

(7.6—5.1), i.e., 2.5 lb. per sq. ft.

As a column of water 1 ft. square and 1 in. high (i.e. pressure=1 in. w.g.) weighs 5.2 lb. the static draught is thus $1 \times \frac{2.5}{5.2}$ i.e., 0.48 in.w.g.

In practice the measured draught will be less than this because of friction losses and loss of energy at the chimney exit. The subject of loss of draught is discussed further in Chapter 10.

The following Table gives the results of a calculation on similar lines for a chimney 100 ft. high (a) with different average chimney temperatures and (b) with air temperatures representing a cold day and a hot day.

TABLE 2

	(A)			(B)	
	60	60	60	32	90.
Outside air temperature : ° F. ..	200	350	500	350	350
Mean chimney temperature : ° F. ..	0.27	0.48	0.64	0.56	0.40
Draught: in.w.g.					

The effect on draught of these various conditions should be noted (see Fig. 2.) The draught is better in cold weather.

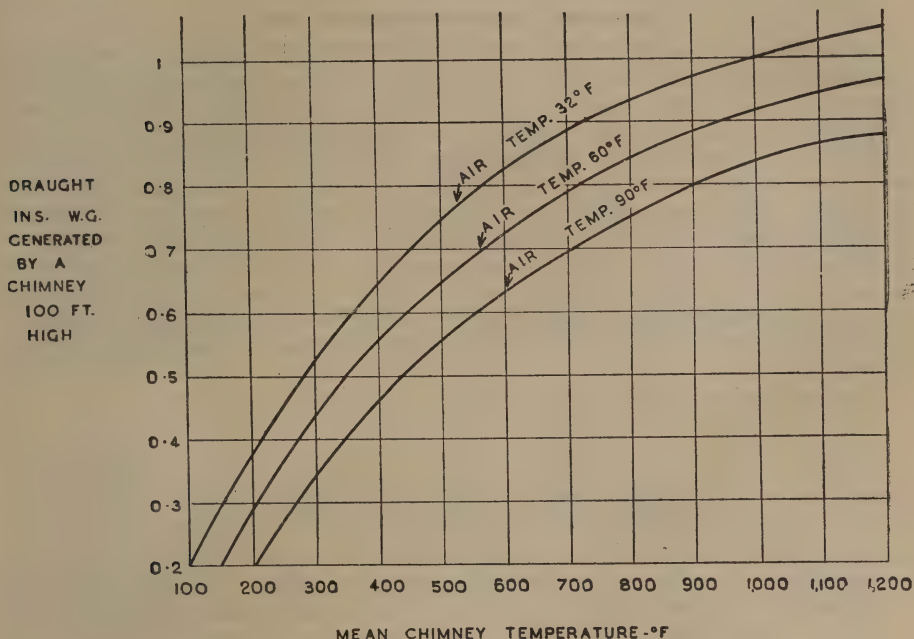


FIG. 2. Effects of gas and air temperature on static draught.

The chimney height depends on the draught required and, bearing in mind that the effectiveness of a chimney will depend on its location and construction, an approximation of the required height can be calculated as follows:

$$H = D \div \left(\frac{7.6}{t_1 + 460} - \frac{7.9}{t_2 + 460} \right)$$

where H = height of chimney : feet,

D = draught: in.w.g.,

t_1 = outer air temperature, e.g., 60° F., 32° F.,

t_2 = mean gas temperature in the chimney, e.g., 200° F.

For a chimney of a given height and having a known mean temperature, this formula can also be used to indicate the draught that should be available.

The mean temperature in the chimney can be deduced from the temperature at the chimney base, by subtracting, from the recorded chimney base temperature, 2 deg. F. for every 3 ft. of height. This is an empirical figure derived from experience; although not applicable to all cases it will be found to give a conservative result that can be safely applied in practice.

The gas velocity that is set up in a system of flues varies directly as the square root of the draught. For practical purposes, the required area of a chimney should be computed on the basis of a flue and chimney velocity of 15 ft. per sec. measured at the working temperature. The gross areas of chimney and flues are calculated on this basis from the probable quantity of gaseous products of combustion deduced from Table 5, Chapter 6, allowing the proper quantity of excess air for the fuel concerned.

To the radius of the chimney as thus determined 2 in. are added to allow for the diminished velocity against the walls.

PRIMARY AND SECONDARY AIR

Air admitted through the fuel bed and giving up its oxygen to effect the preliminary part of the operation of burning the fuel is called *primary air*. For gaseous and liquid fuels and for powdered coal the primary air enters the furnace mixed with the fuel; in the case of solid fuels it passes through the fuel bed. The rest of the air necessary for completing combustion is admitted separately as *secondary air*. This secondary air helps to complete the combustion of the volatile matter, including smoke, expelled from the solid fuel during the preliminary stage of its combustion. Secondary air is generally admitted above the fuel bed. Some secondary air may find its way up the side or back of the fuel bed, or as is only too often the case through thin areas in it.

It will thus be seen that combustion of a solid fuel takes place in two stages. Further supplies of air, sometimes designated as *tertiary air* may even be admitted.

The fuel bed may be divided into zones, as shown in Figure 3.

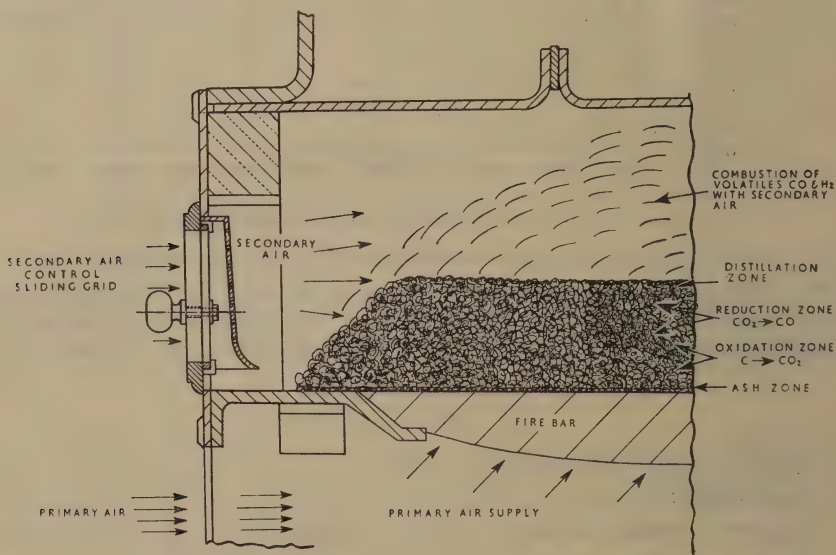
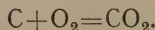
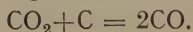


FIG. 3. Fuel bed zones in overfeed firing.

At the bottom lies the bed of ash. Above this is the primary oxidation zone in which the reaction between carbon (in the fuel) and oxygen (in the air) form carbon dioxide thus :



If the fire bed is deep enough, the carbon dioxide is *reduced* by passing over more hot carbon or coke, forming carbon monoxide thus:



Since carbon monoxide is an inflammable (i.e., combustible) gas, secondary air is required to burn it. Unless it burns to form CO_2 less heat is evolved than would otherwise be the case. The escape of carbon monoxide unburnt into the flue gases represents a serious waste of the heating value of the fuel. In a shallow fuel bed very little carbon monoxide is formed.

Above this zone there is the distillation zone in which the raw coal, heated by the gases rising through it and by radiation from the lower zone, is distilled and carbonized, giving off tarry gases and vapours, as well as smoke, all of which rise into the combustion space above the fuel bed. They require secondary air to complete their combustion. Low-volatile fuels such as coke and anthracite have little or no distillation zone, nevertheless secondary air is required to burn off any CO formed.

Complete combustion of solid fuels is thus brought about by the use of both primary and secondary air, efficient combustion depending on the correct proportioning of the two. Experience shows that the most frequent cause of smoke emission is an inadequate supply of secondary air. In order to obtain maximum efficiency, it must be so controlled and mixed with the gases leaving the fuel bed that complete combustion takes place within the appointed space and with the use of as little *excess air* (see below) as possible.

The principles governing the adjustment of primary and secondary air will be better understood by considering the subject of the flow of gases, and especially the flow of air through fuel beds.

FLOW OF AIR THROUGH FUEL BEDS

In a fuel bed the passages for a flow of air are dependent upon the size of the fuel and the character of the changes that are taking place; these changes, in turn, must vary with changes in velocity. Furthermore, during the process of combustion when carbon monoxide or carbon dioxide and steam are being formed, a change of volume occurs according to the proportions of these gases produced, and these vary throughout the fuel bed according to conditions. The volume of the gases is affected by the temperature in the fuel bed, so that the whole course of the flow becomes a matter of some complexity; it cannot be related to any simple statement of principles.

It has been shown by experiment that the pressure drop, p , through a fuel bed obeys partly the streamline law in which $p \propto v$ (where v is the air velocity), and partly the turbulent law in which $p \propto v^2$. The overall effect depends on the nature of the fuel bed and the rate of air flow, but can be represented by the expression $p \propto v^n$ where n may be about 1.7.

It is convenient, however, to think of the flow as turbulent, i.e. $p \propto v^2$. Hence if v is doubled, as a result of doubling the combustion rate, the pressure drop across the fuel bed is quadrupled.

This means that to double the rate of combustion—which involves doubling the amount of air supplied to the furnace—the draught must be quadrupled.

EXCESS AIR

The relative ease with which secondary air is drawn into a furnace emphasises the importance of controlling it. The methods of calculation of flue gas composition (from analyses) given in Chapter 6, enable the amount of excess air used and the total quantity of flue gases produced from a given quantity of fuel to be deduced from the flue gas analysis. The exact figures will depend upon the analytical composition of the fuel, but guidance can be obtained from Fig. 4.

If carbon monoxide or any other combustible gas reaches the flue unburnt, its presence is a proof of the loss of potential heat; this should not be allowed to happen. In good boiler practice the percentage of CO_2 is within limits a good indication of the efficiency of stoking; if the amount of CO_2 is in the range 12–14 per cent. (using coal) the stoking can be assumed to be satisfactory. The actual figure depends on the character of the fuel and the type of equipment used.

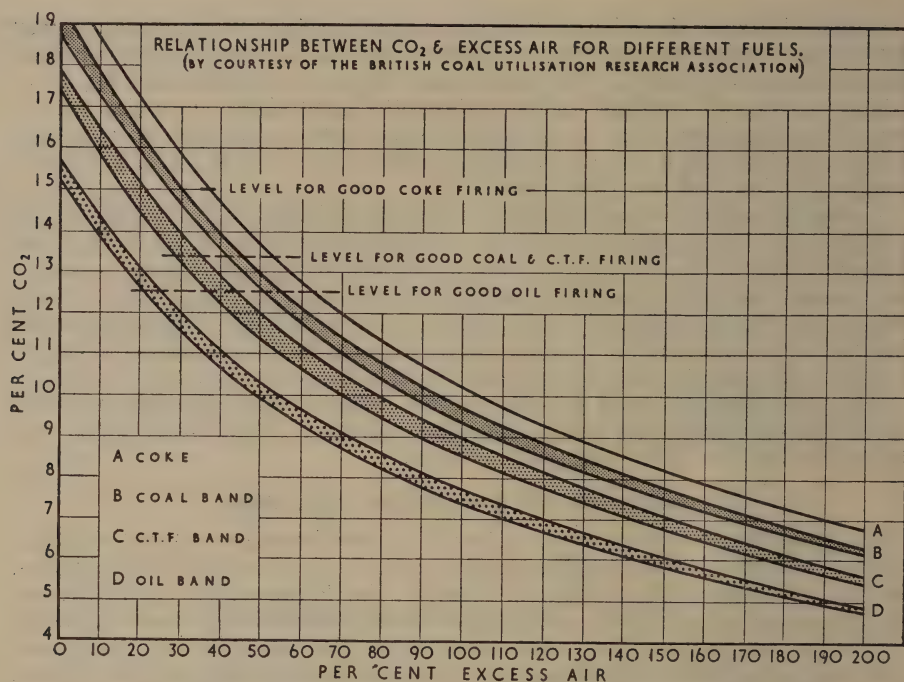


FIG. 4. Relationship between CO₂ content and excess air.

If over 14 per cent. of CO₂ is present, there may be a risk of unburnt gases such as carbon monoxide and hydrogen being also present, with a consequent loss of efficiency. The heat losses equivalent to the presence of 0.1 per cent. of such gases in a flue gas are, respectively, carbon monoxide: 0.47 per cent.; hydrogen: 0.48 per cent.; methane: 1.52 per cent.

The effect on efficiency of using too much or too little excess air is well illustrated in diagrammatic form in Fig. 5 which, with Fig. 6, is based on trials carried out by the Fuel Research Station staff on a Lancashire boiler burning a bituminous coal. In this case maximum efficiency was obtained with 34 per cent. of excess air. Increasing the excess air to 120 per cent. caused the efficiency to fall from 72 per cent. to 60 per cent.; decreasing the excess air to 15 per cent. produced the same drop in efficiency. As shown in Fig. 6, the maximum efficiency of the boiler was obtained with no smoke emission. When the smoke density was increased by restricting the supply of secondary air the efficiency fell rapidly, mainly as a result of the loss of potential heat in the combustible gases passing away with the smoke. This was many times that lost in the visible smoke, and with a black smoke (Ringelmann No. 5) was equivalent to about 14 per cent. of the potential heat in the fuel fired.

For the efficient working of Lancashire boilers and similar installations, the CO₂ in the flue gas should generally be about 12 per cent. A certain amount of excess air is in practice unavoidable and, indeed, for all practical purposes, essential. The use of too much excess air, with its concomitant waste, must be guarded against.

The heat carried away in the waste gases depends upon their heat capacity which, in turn, depends upon their specific heats, quantities and temperature, but mainly the latter two. In practice, all the useful heat in the fuel can never be abstracted by the boiler and its auxiliaries. For example, economisers or air heaters may cool the gases to about 300° F. (the range being between

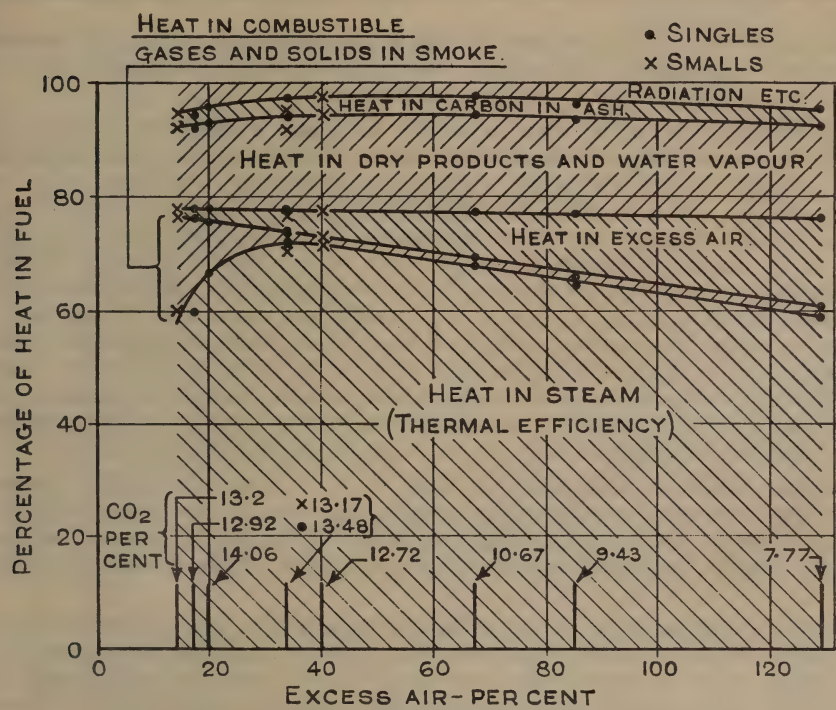


FIG. 5. Effect of excess air on the heat account.

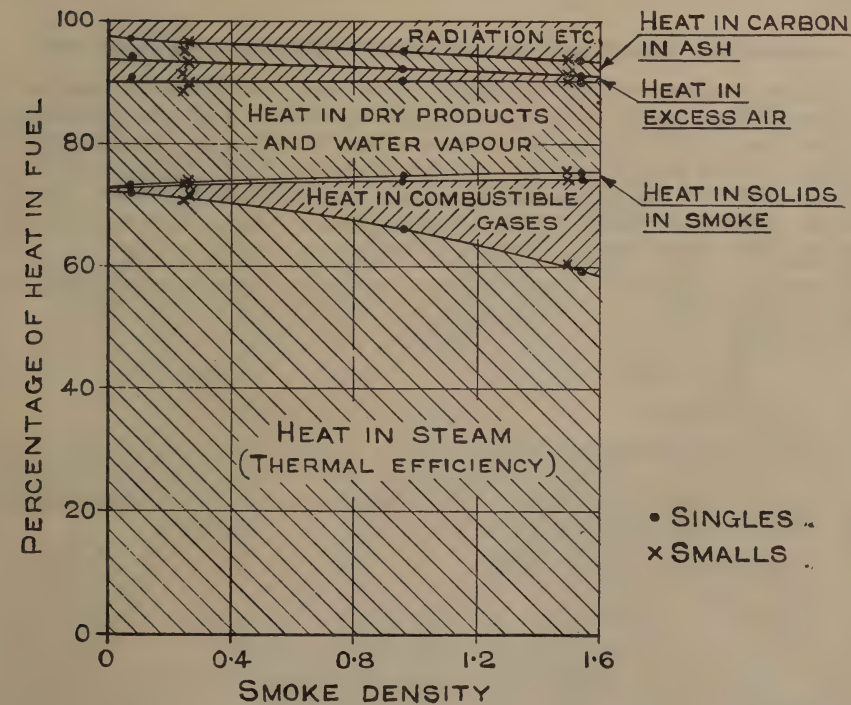


FIG. 6. Effect of smoke on the heat account.

250 and 450° F.). If the volume of the waste gases is increased by unused excess air, the amount of the heat loss in the chimney corresponding to a given rate of combustion of coal, is also increased.

For furnace work it is often necessary to create a reducing atmosphere *within the furnace*, e.g., in some metallurgical practice and in some kilns. For this purpose, the amount of air admitted is deliberately regulated so as to be insufficient and to result in the production of a small amount—up to 2 per cent.—of carbon monoxide in the flue gases. If the fuel used is coal gas, this may be accompanied by about 2.4 per cent. of hydrogen. To attain perfect combustion, without the production of CO or hydrogen, the amount of excess air essential when firing with coal is generally not more than 50 per cent.; under specially favourable conditions it may be as little as 30 per cent. Powdered fuel can be burned with less than 20 per cent. of excess air, oil fuel with less than 15 per cent. and gaseous fuels with less than 10 per cent. of excess air or, with careful regulation, almost the theoretical quantity. These figures can, however, be achieved only by very careful and expert operation.

In this connection it should be realised that efforts to restrict the amount of excess air used in order to obtain higher thermal efficiency may entail a risk of thermal loss through small quantities of unconsumed gases passing into the flue. In general, it is better to use too much excess air than to use too little.

In all cases the essential factor is the degree of mixing of combustibles from the fuel and the air within the combustion chamber. Satisfactory mixing can practically never be secured by hand firing. Badly operated boilers may all too frequently be found to be using 100–200 per cent. of excess air, or even more.

GRAPHICAL CALCULATION OF HEAT LOSSES IN THE FLUE GAS

Detailed methods of calculating flue gas losses are given in Chapter 7. To simplify these methods in practice, charts similar to Fig. 2 in that chapter may be constructed and the heat content of the flue gases may be read directly from the charts when the CO_2 content of the gases (or the amount of excess air used) and the flue gas temperatures are known. Since the maximum CO_2 content varies for different types of fuel, depending on the carbon and hydrogen contents, charts must be calculated for the particular fuel used.

To avoid the labour of calculating complete sets of curves for each fuel, the more comprehensive graphical method of Figures 7 and 8 can be used.

Figure 7 as here reproduced is drawn for four fuels :

- | | |
|----------------------|---------------------|
| (a) pure carbon, | (c) a fuel oil, and |
| (b) bituminous coal, | (d) a coal gas. |

It can be used, however, for fuels of slightly different compositions but of the same types. It cannot be used for gases such as producer gas and blast furnace gas, for which the more elaborate curves previously described must be drawn, otherwise the calculations must be made from first principles.

To construct Fig. 7 the straight line diagonally across the chart from the point (0,0) to the point (21, 21) is taken as the basis. This line represents the theoretical CO_2 content for the particular fuel when no excess air is used. On this line a point is marked corresponding to the theoretical CO_2 content of the flue gas for the particular fuel used, i.e. using the theoretical quantity of air, and no excess; thus for the fuels illustrated in the chart the points selected are:

					Per cent. CO ₂
Coke oven gas and town's gas	..	..	..	..	11.5
Fuel oil .. .. .	..	..	..	..	15.5
Bituminous coal .. .. .	..	..	..	..	18.5
Pure carbon .. .. .	..	..	..	..	21.0

If coke were used, the point 20.5 would be selected instead of 21.

$$\text{MAXIMUM CO}_2 \text{ CONTENT (DRY)} = \frac{21C}{C + 2.37H} \%$$

WHERE
C = % CARBON CONTENT OF FUEL
H = % AVAILABLE HYDROGEN CONTENT OF FUEL

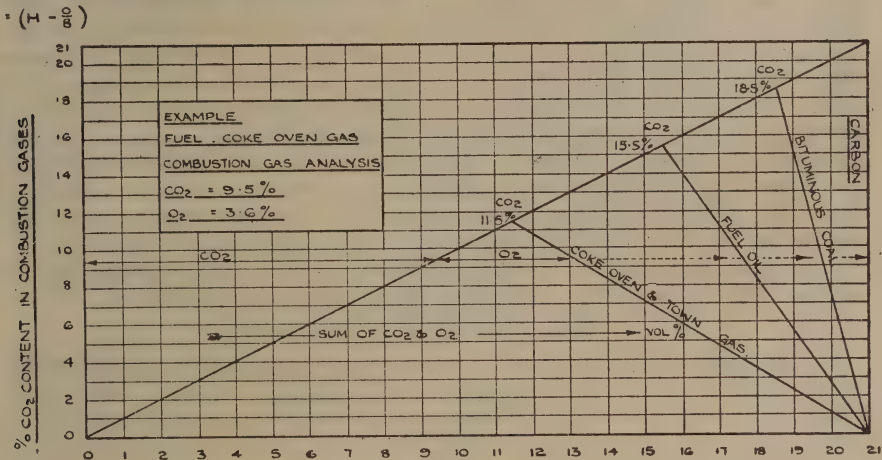


FIG. 7. Relation between CO₂ and O₂ in flue gases.

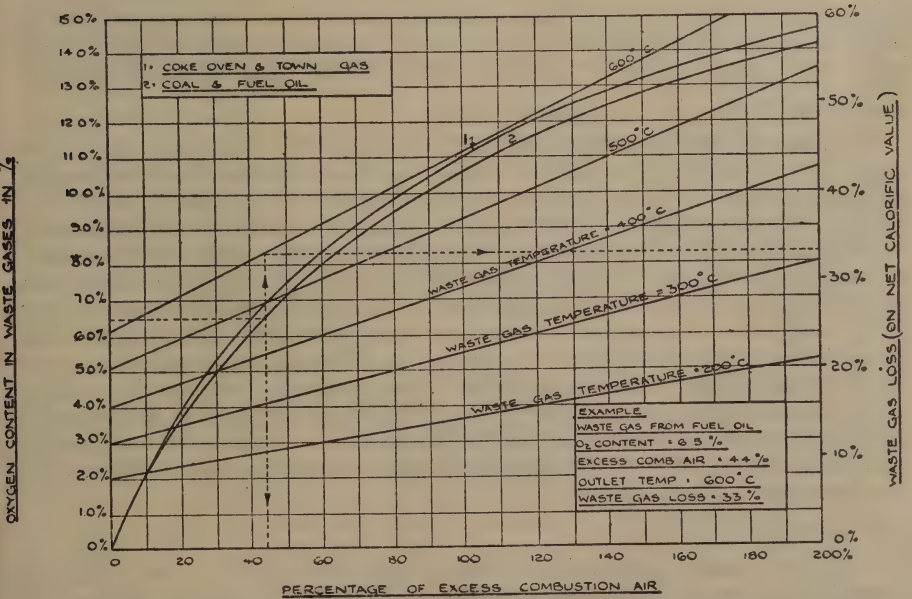


FIG. 8. Chart relating loss in flue gases with O₂ content of the gas.

The flue gas loss does not include that due to the latent heat of the water vapour formed by the combustion of hydrogen in the fuel.

Some town and coke oven gases have a theoretical flue gas CO_2 figure of 10.5 per cent., but some may be as high as 13 per cent. Whatever the figure may be for the particular fuel in question, the position of the *maximum* CO_2 content by analysis (i.e., with the water vapour condensed out of the gas) is marked on the basic diagonal line. This point is then joined to the point (21, 0) in the bottom right hand corner of the chart, as has been done for the four fuels taken as typical.

The method of using Figs. 7 and 8 is best explained by an example. Let it be assumed that the fuel used is an oil fuel of such a composition that the theoretical flue gas contains 15.5 per cent. of CO_2 and that the flue gas temperature at the outlet is 572°F. (300°C.). The actual CO_2 content of the gases is 10 per cent. From Fig. 7 it is found by measuring horizontally from 10 per cent. on the extreme left-hand side, that with 10 per cent. of CO_2 the flue gases will contain 7.5 per cent. of O_2 . From Fig. 8, curve No. 2, it is seen that 7.5 per cent. of O_2 indicates 55 per cent. of excess combustion air. Then from the point where the waste gas temperature curve for 572°F. (300°C.) cuts the vertical line from 55 per cent. (excess air) and reading horizontally on the extreme right it is found that the stack loss is 16.5 per cent. of the net C.V. of the oil. The figures for another example, for an oxygen content of 6.5 per cent. and indicated by the dotted lines in Fig. 8, are given in an inset in the figure.

If an allowance of 5 per cent. be made for radiation and similar losses, the thermal efficiency of heat utilization would work out as follows:

$$100 - 16.5 - 5, \text{ i.e. } 78.5 \text{ per cent.}$$

On the gross C.V. of the fuel, the stack and radiation loss would be :

$$\frac{(16.5 + 5) \times \text{net C.V.}}{\text{gross C.V.}}$$

TIME, TURBULENCE AND TEMPERATURE

The right quantity of air having been introduced into the furnace, divided when necessary into the right proportions of primary and secondary air, the important factors of *time, temperature and turbulence* may be considered.

The Time Factor in Combustion

All chemical reactions require a definite time for their completion, depending upon several factors, the inherent nature of the reaction, the temperature, and the difficulty of bringing the reacting substances into contact sufficiently quickly. Consequently, sufficient time must be allowed for combustion whether in a solid fuel bed or during gaseous combustion of the volatile matter or the combustion of the gaseous fuel. With solid fuel, a bed that is too thin, or thin in relation to the size of the fuel used, lets air pass through without being used because there is not adequate contact between the oxygen of the air and the carbon of the fuel. In gaseous combustion, the combustion space must be adequate to provide sufficient time. For rapid combustion, the air and gas (or in pulverized fuel firing, the powdered coal) must be as intimately mixed as possible as soon as they enter the furnace. If mixing is not intimate, the flame may be very long, extending even outside the furnace proper and into the flues.

Turbulence

In boiler furnaces, the volatile matter is evolved from the coal, and the secondary air may tend to pass over above the volatiles but not mixing with them as shown in Fig. 9. When this happens, mixing may be promoted by the use of a jet of steam or air directed downwards at an angle.

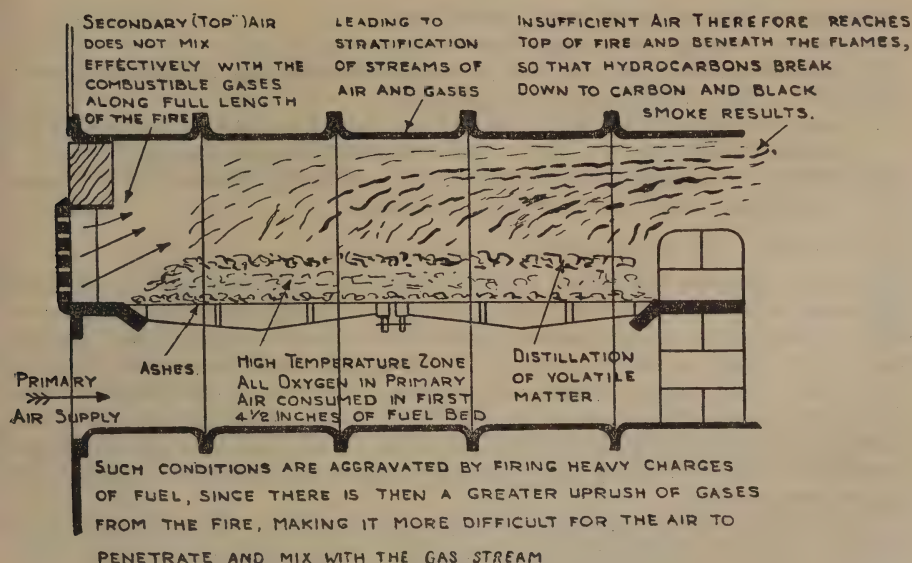


FIG. 9. Stratification in combustion gases in a boiler furnace.

Temperature

Combustion cannot take place until the temperature of the ignition of the fuel concerned is not only reached but exceeded. When there are cold surfaces close to the grate, it is particularly necessary to mix the secondary air of the combustible gases as completely and quickly as possible. It is in such conditions that the use of pre-heated secondary air would be advantageous, whether it is actually feasible in practice is perhaps questionable. In certain furnaces and kilns, on the other hand, where long flames may be specifically required, such early mixing may have to be avoided.

The speed of combustion reactions increases much more rapidly than does the rise of temperature at which combustion takes place. Consequently pre-heating of air assists in attaining rapid combustion. In boiler practice, however, high efficiencies may be attained without the use of pre-heat.

The chilling effect of cold surfaces is a very important factor. The temperature of flames from burning coal is over $2,000^{\circ}\text{F}$. ($1,090^{\circ}\text{C}$.), or even higher, according to the temperature within the fuel bed and the distance which the flame has travelled from the incandescent fuel. The temperature of the boiler metal, on the other hand, is generally little higher than that of saturated steam, generally below 475°F .

In a metallurgical furnace the stock is generally charged cold. If flames impinge on these cold surfaces, combustion will be arrested; as a result carbon monoxide and hydrogen may go forward into the flue gases. Hydrocarbon gases may be decomposed, liberating free carbon, and thus produce smoke.

This chilling effect of cool surfaces on flames may go even farther.

If a basin of cold water is held in a luminous flame of coal gas, the basin quickly becomes covered with a film of soot. In a similar manner soot may be deposited on cold metal surfaces. Not only does the chilling effect and liberation of free carbon, as soot, represent loss of fuel, but the soot film has a low thermal conductivity. Although the film is a good heat-absorbing surface, the rate of heat transfer from the flame to the vessel being heated may be substantially reduced.

Chilling of furnace flames may result from :

- (a) heavy charges at infrequent intervals;
- (b) excessive air supply, e.g., by prolonging the opening of furnace doors ;
- (c) a long flame impinging on to the metal;
- (d) thermal features that force the burning gases into intimate contact with cooler metals, e.g. too high a fire-bridge in the boiler furnace;
- (e) design of the plant. The circular section of boiler furnaces makes them particularly liable to this type of chilling.

Size of Coal. The "Conditioning" of Small Coal

In order to make the fullest use of primary air it is essential to have as uniform a fuel bed as possible, that is, a fuel bed offering as uniform resistance to the passage of air as it is possible to achieve in practice. A small-size, graded fuel gives the best air distribution. Undue proportions of fines present in slack coal increase the fuel bed resistance and cause uneven air distribution. This is due largely to segregation, i.e., separation of larger material from the fines. Some parts of the fuel bed, offering less initial resistance to the air, burn out sooner than others, leaving bare patches through which unused primary air rushes uncontrolled.

This difficulty can be overcome, to a great extent, by wetting the coal. The amount of water to be added should be about 1 per cent. for every 10 per cent. of fines in the coal passing through $\frac{1}{8}$ in. mesh.

The use of fine coal with too low a moisture content can result in the loss of more than 30 per cent. of the evaporative capacity of the boiler. In practice the coal should, after wetting, just "ball," in the hand when gently squeezed, without surplus water being expelled.

For firing on chain-grate stokers it is essential that slack be uniformly wetted. Since this is a difficult operation in practice, there is an advantage in using washed slack instead of dry slack, because the former will have become evenly wetted. The addition of water results in a small lowering of the efficiency, to the extent of about 0.1 per cent. for each 1 per cent. of added water, but this is more than fully recovered as a result of the improved combustion conditions.

CAKING PROPERTIES OF THE COAL

The caking properties of a coal may have a great influence on the ease of combustion. It often happens that strong caking properties are accompanied by excessive fineness and in such cases attention to the moisture content of the coal will to a considerable extent overcome troubles traditional with this kind of fuel. By contrast with non-caking coals, caking coals tend to give an open, irregular fuel bed composed of large masses of coke separated by wide fissures, which result in poor contact between air and fuel.

THE COMBUSTION OF COKE

In the preceding section, the effects of the most important factors governing the combustion of coal—its size and volatile content and the depth of the fuel bed—were considered. Coke yields so little volatile matter that the influence of volatiles on combustion can be neglected; but other factors are as important as in the case of coal.

Depth of Fuel Bed

Table 3 shows the composition of the gas at different levels in a coke fuel bed. It will be seen from the figures that it is possible to distinguish oxidation and distillation zones similar to those described in considering the coal fuel bed.

TABLE 3
GAS COMPOSITION IN A COKE FUEL BED

Distance from bottom of fuel bed	Composition by volume—per cent.					
	Size of coke 3½ × 3 in.			Size of coke 1½ × 1 in.		
	CO ₂	O ₂	CO	CO ₂	O ₂	CO
In.						
12	14.0	0.5	6.4	5.4	0.4	24.9
6	16.0	4.0	0.5	15.1	1.1	7.0
4½	12.0	7.5	1.0	16.3	1.4	5.3
3	—	—	—	16.8	2.9	2.7
1½	5.0	13.5	1.0	11.5	8.0	0.8

If the size of the pieces of fuel is sufficiently great, some air may pass through the bed without contact; this is known as *channelling*. When this happens, the unused air functions as secondary air.

The smaller sizes of coke have the disadvantage of tending to form objectionable clinker. This is partly due to the fact that the ash is evenly distributed through the pieces of coke, and partly due to their small size. Both lead to close contact, a primary cause of clinker formation. Difficulty with clinker formation may be lessened by using large fuel. This is also true of anthracite.

Reactivity and Combustibility of Coke

An important characteristic of coke is that different types react at different rates with oxygen and CO₂. The results given in Table 3 relate to metallurgical coke. Using gas coke, the results might be somewhat different in that more rapid combustion would probably occur in the lowest zone and more rapid reduction (to CO) in the next zone.

Coke burns more slowly than coal (owing to the very low content of volatile matter) and may require more draught because a much greater proportion of primary air is needed. In boiler practice it is frequently found that enough secondary air is derived from what passes through or round the grate or enters through badly fitting doors, and that the regular secondary air slides should be closed. This applies also to anthracite. The composition of the combustion gases from coke differs from those from coal (see Table 3).

Much more carbon (as much as 50% more) has to be burnt than when bituminous coal is the fuel. As the area of the grate is fixed the only way to meet the two distinct and separate requirements—the larger volume of primary air, and the increased pressure—is by means of forced draught. Without forced draught, the boiler is de-rated to the point at which the maximum air flow takes place through the fuel bed.

SMOKE

Smoke within the furnace consists mainly of the tarry distillation products of the coal which escape before combustion is complete. When the amount of volatile matter in the coal becomes small the quantity of tar evolved from the coal becomes less, the liability for smoke to be formed also becomes less. This accounts for the smokeless characteristics of Welsh smokeless coal, anthracite and coke.

There are two forms of smoke :

- (1) brown smoke, which is mostly tarry matter given off at relatively low temperatures immediately after fresh coal has been fired on to a hot fuel bed and,

- (2) black smoke, which consists largely of particles of carbon derived from the "cracking" and subsequent quenching of hydrocarbon gases at a high temperature (regarding the process of *cracking* see Chapter 4).

Brown smoke is relatively easy to consume; black smoke is less easy to deal with, and excess air, even if pre-heated, is not necessarily able to complete its combustion. It must also be subjected to a high temperature when in contact with the pre-heated excess air. The two smokes may, of course, be present simultaneously.

To consume smoke, there must be sufficient secondary air, adequate mixing of the air with the volatiles, and a sufficiently high temperature zone in the combustion space to ensure that combustion takes place rapidly before the gases come into contact with any colder surfaces.

The *amount* of carbon in dense smoke is small; the real danger of waste due to smoke lies in the possible presence of unconsumed invisible combustible gases. On the other hand, attempts to avoid the production of smoke by using unnecessarily large amounts of excess air can cause more serious heat losses. A chimney serving a furnace working on bituminous coal should be neither quite clear nor definitely smoky; the plume should be just visible as a light haze.

THE COMBUSTION PROCESS IN OVERFEED FIRING

The process of combustion varies from one form of appliance to another and the following examples indicate how variations in the fuel bed conditions affect the proportions of primary air and secondary air required.

With a thick fuel bed (see Fig. 3), where the raw coal is fed on to the top of the hot fuel, most of the volatile matter may be driven off before the carbonaceous residue descends to the lower levels, where an excess of oxygen is present. Under such conditions, the volatile matter distilled off unburnt requires a supply of secondary air, over the fuel bed, for its combustion.

With a thin fuel bed, of the order of 3 in. in depth—as on a sprinkler stoker there is no reduction zone; distillation and combustion occur together. A proportion of the volatile matter is burned by the primary air and much less secondary air is required.

With a chain-grate stoker, very little volatile matter is given off unburned, except in the extreme front of the grate during the process of ignition (see Fig. 10). Most of it is burned off just above the advancing ignition plane, though part of the CO_2 is subsequently reduced to CO in the upper levels of the fuel bed, and still requires air for complete combustion.

CLINKER FORMATION

Masses of ash, and sometimes of cinders, partly compacted by local melting, are known as *clinker*.

One of the main difficulties in maintaining a uniform resistance of the fuel bed is the formation of clinker, masses of which prevent the flow of air to those portions of the grate which they cover; greater work is thus thrown on to the rest of the grate. The draught required for a given combustion rate is considerably increased by the presence of clinker and may blow fuel off the grate. A discussion of clinker and its formation is thus an essential part of the general subject of combustion.

The ash formed when coal is burned is a complex mixture derived partly from the incombustible mineral matter in the plants from which the coal was formed, partly from the earthy materials with which the plant remains were associated and partly from stony material—for example so-called *shale*, stone bands, etc.—mined along with the coal. When the coal is burned, each of

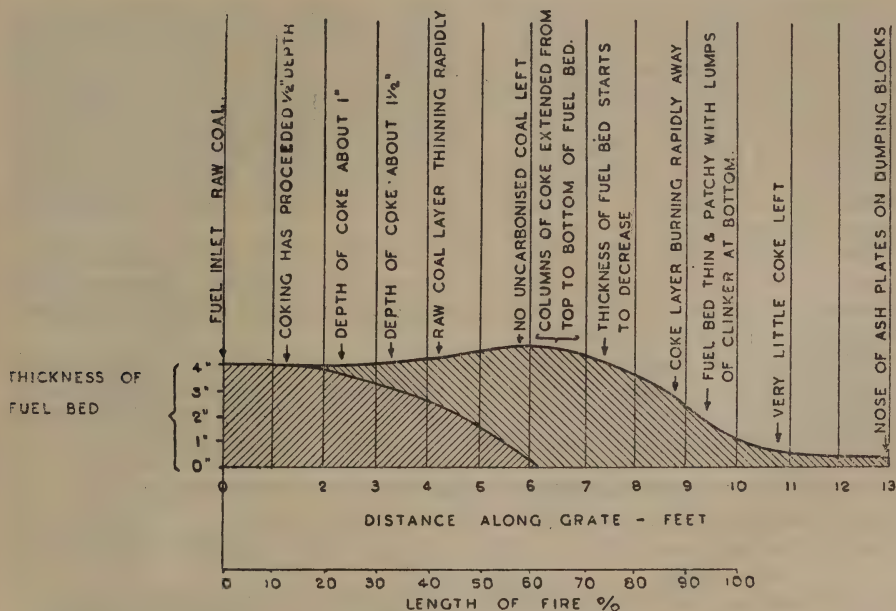


FIG. 10. Combustion on a chain-grate stoker.

(B. M. Thornton, *J. Inst. Fuel*, viii, 13.)

these substances contributes its own quota of ash. Any one of these may have a relatively low melting-point; but if such easily fusible pieces or particles do melt, adjoining pieces or masses of ash may become cemented together with them. Furthermore, although no one portion of ash may have a low melting-point, if two or more quotas become intimately mixed the mixture may have a low melting point and clinker will form.

It will be seen, from the preceding, that a coal may produce clinker under some conditions but not under other conditions. Slack coal might conceivably more readily produce clinker than large size coal from the same seam.

The behaviour of individual chemical constituents of a coal ash is both interesting and important. As an example, the higher oxide of iron, ferric oxide (Fe_2O_3), does not tend to combine with silica (SiO_2) to form a fusible clinker. The lower oxide of iron, however, ferrous oxide (FeO), which is formed under *reducing conditions* such as sometimes exist in a furnace, e.g., in a fuel bed, *does* tend to form a silicate, by combining with silica, and that silicate has a very low melting point—it is readily fusible. The intermediate oxide of iron (Fe_3O_4), also likely to be present, behaves somewhat as FeO ; furthermore, it is itself readily fusible, i.e., without combining with silica. Consequently under reducing or semi-reducing conditions within the furnace an ash containing relatively large proportions of iron oxide may well contribute materially to clinker trouble.

Certain other silicates, either separately or in combination, may also fuse readily and help to produce clinker—sometimes irrespective of whether the furnace atmosphere is an oxidising one or a reducing one.

It will thus be seen that the matter is complex, and it is difficult—perhaps unwise within the scope of this book—to attempt a general correlation between the mineral or chemical composition of the ash and the risk of clinker formation.

In order to obtain an indication of tendency to form clinker it is common to determine the melting-point of coal ash. This is done by grinding the ash to a fine powder, making a cone of the powder thus produced, and determining its softening temperature and melting-point by heating the cone in a furnace specially designed for the purpose. Arrangements are made for creating an oxidising or a reducing atmosphere within the furnace, as desired. The fine grinding to which the ash is subjected for this test mixes all the constituents intimately; consequently, the cone may well melt at a lower temperature than the unpowdered ash would have done.

The expression *melting-point* has been used above. Strictly speaking, the cone first softens at the edges in the furnace, then becomes deformed and ultimately collapses and becomes quite fluid. It is hardly correct to suggest that there is a sharp melting-point.

Although it will thus be seen that the fusibility of a coal ash, as determined in the laboratory, cannot be regarded as an entirely reliable indication of liability to form clinker, the following figures are given as a result of work done in this direction, coal ashes being classified in three groups.

COAL ASH FUSIBILITY AND CLINKER FORMATION

Group 1 Melting-point over $1,400^{\circ}\text{C}$.—No clinker trouble.

Group 2 Melting-point $1,200$ – $1,400^{\circ}\text{C}$.—Clinker may form but not likely to be serious.

Group 3 Melting-point below $1,200^{\circ}\text{C}$.—Clinkering troubles likely.

The ash melting-points of most British coals lie between $1,050^{\circ}$ and $1,350^{\circ}\text{C}$, although there are notable exceptions such as the ashes of durains, many of which melt at over $1,450^{\circ}\text{C}$. Some of the ash constituents will usually melt below the temperature of the fuel bed ($1,300$ – $1,500^{\circ}\text{C}$.) and will thus afford a basis for clinker formation.

Table 4 gives the laboratory ash fusion points (in a semi-reducing atmosphere) of a representative selection of saleable coal from each of the National Coal Board Divisions.

TABLE 4
NUMBER OF COALS WITH ASH MELTING-POINTS
BETWEEN STATED LIMITS

<i>Ash Fusion Temperature $^{\circ}\text{C}$.</i>	1000– 1100	1110– 1200	1210– 1300	1310– 1400	<i>Above 1400</i>	<i>Total</i>
Scotland	—	3	2	6	80	91
Northern (N. & C.)	—	24	40	54	47	165
Durham	—	23	102	89	135	349
North Eastern	—	52	144	39	9	244
North Western	20	135	41	13	1	210
East Midlands	25	239	275	92	14	645
West Midlands	3	49	99	40	23	214
South Western	—	28	78	96	117	319
South Eastern	—	4	5	4	—	13
	48	557	786	433	426	2,250

It will be seen from this table that in general the ash of Scottish coals is particularly infusible. Durham and South Western Divisions also provide a large proportion of coals with high ash fusibilities, but in the central block of coalfields, which produce nearly 60 per cent. of the total output of British coal, ash fusibility is lower, particularly in the North Western Division where most of the coals show values below $1,200^{\circ}\text{C}$. It should be remembered, however, that for some combustion processes (e.g. slag-tap and cyclone furnaces) low ash fusibility, which is normally combined with low viscosity of fused ash, is advantageous.

Whether a given ash will form clinker or not depends on several circumstances ;

(a) The distribution of the mineral matter in the coal.

Clinker may form through complete fusion of the ash, which will lead to the formation of large masses of clinker, or by the cementing together of pieces of "shale" themselves relatively infusible, in the manner previously described. By a combination of sizing tests and float-and-sink tests, there can be obtained from coals certain "fractions" which melt much below the average melting-point temperature. Thus, even in a large piece of relatively clean coal there may be fusible and infusible constituents not blended in a uniform manner. They may be distributed differently :

- (i) in different parts of the seam,
- and (ii) in different laminations in each lump of coal.

(b) The atmosphere to which the coal is exposed.

The melting-point or melting range of a coal ash determined in a reducing atmosphere is always somewhat lower than that determined in an oxidising atmosphere because in the reducing atmosphere Fe_2O_3 becomes reduced to FeO .

It has been found that the difference between the two temperatures in question, for coal ashes "melting" above $1,200^{\circ}\text{C}$., as determined in an oxidising atmosphere, is from 30 deg. C. to 50 deg. C.; for other more readily fusible ashes the differences are greater.

In ashes from boilers and furnaces the iron is almost completely reduced to the *ferrous* state, so conditions are the worst possible in respect of clinker formation. A thin bed is more likely to produce an oxidised ash and thus lessen clinker formation.

(c) The extent to which the mineral matter becomes mixed with the fuel in the hottest zone of the fuel bed.

Disturbance of the fuel bed during combustion tends to raise mineral matter from the grate (where it is cooled by incoming air) into the hottest part of the fire. Slicing and poking should be kept to a minimum. In underfeed stoking the fuel bed is kept in more or less disturbed motion, thus assisting the formation of clinker, whereas on chain grates, where the fuel bed is moved bodily forwards, disturbance is at a minimum.

The effect of contact between the several particles of coal must also be considered. This is greater in proportion as the coal decreases in size; the smaller the coal the greater is the risk of clinker formation. It has also been suggested that very finely divided inherent ash may have a greater effect in promoting clinker formation than the ash from the associated "dirt." This may be due to the alkalis generally present.

In those zones where the coal is burning most actively, the temperature will be the highest. Much of the ash will then be within the coal, and ash particles may not be so readily brought into contact with each other as in the last stage of combustion, when most of the carbon has disappeared. In this stage, however, the combustion is less intense and the temperature will be lower.

Experimental evidence suggests that both with coal and coke, clinker formation occurs more than 4 in. above the bed of the grate; as it sinks through the fuel bed, the clinker solidifies below that 4 in. level².

(d) The time during which the ash is subjected to a high temperature.

Chemical reactions may occur, with the formation of mixtures of low melting-point *provided there is sufficient time for them to form.*

(e) In order that clinker will form to any appreciable extent conditions must be such as to produce enough slag of sufficient fluidity to make it run together in masses, or to percolate through other masses of less fusible mineral matter, binding them into aggregates.

(f) Pre-heated air may, though raising the fuel bed temperature, tend to promote clinker formation.

Certain aspects of the subject are dealt with in Chapter 23. Refractory and Insulating Materials under "The Action of Slags."

FIREBAR COOLING

A period of moderate or light load on a boiler immediately following a period of heavy load entails a risk of serious danger to firebars because of overheating. During periods of normal and heavy load the firebars are kept reasonably cool by the incoming primary air. When the load is heavy the temperature of the fuel bed rises to a very high value. As soon as the demand slackens off the amount of incoming primary air becomes less and, in consequence, there is not the same cooling effect. The hot fuel bed raises the temperature of the firebars to red heat and distortion and other damage ensues. There is a similar though less risk during banked conditions, when sufficient primary air enters to keep the fuel bed hot but not enough to keep the firebars cool. Under both conditions there is also risk of clinker formation close to the firebars, with added danger of damage to them.

Various expedients are adopted to cope with these difficulties; these include water sprays and steam jets.

Water sprays are applied under fire grates,

(a) to lower the grate temperature

and (b) to lower the fuel bed temperature

in order to lessen clinker formation.

Steam used for cooling purposes,

(a) removes sensible heat from the grate and from the fuel bed by mere physical contact

and (b) acts on some of the carbon in the fuel to produce water gas, the endothermic reaction bringing about rapid lowering of temperature.

It should be noted that this use of steam jets is quite distinct from their use for creating draught. (See Chapter 11.)

If water is used instead of steam the additional cooling achieved by raising its temperature to boiling point, and by the latent heat of vaporization represents, of course, a very much greater cooling. The advantage in using water sprays instead of steam jets is obvious.

From the discussion in Chapter 7 of the thermal effects of the water gas reaction, assuming that (as is likely), of the steam used (say 0.3 lb. of coal) not more than half is decomposed and also that the gases and undecomposed steam leave the fuel bed at about 1,650° F. (900° C.) the total cooling effect per lb. of coal burnt should be between 1,104 and 774 B.t.u. using water sprays and between 772 and 443 B.t.u. using steam jets.

The quantity of water required for cooling has been found by Thornton³ to be only one-half to one-third that of the steam needed. Thornton's figures obtained on an Economic boiler of 15,000 lb./hr. are as follows :

				lb.
Gross steam generated, per hour	..	..	..	15,000
Evaporation per lb. of coal	..	..	..	7.5
				Coal required for 1,000 lb. of steam
(a) No cooling of fuel bed	..	..	..	133
(b) Cooling with 860 lb. steam per hour	..	..	..	140.5
(c) Cooling with 600 lb. steam per hour	..	..	..	138.5
(d) Cooling with water sprays 270 lb. per hour	..	..	..	135

Experimental evidence shows that the effect of saturating at 50–60° C., the air blast of a gas producer with steam, involving the use of 0.3–0.4 lb. of steam per lb. of coal gasified, is to lower the hot zone temperature by about 300 deg. C. (540 deg. F.), i.e. from 1,400° C. to 1,100° C. (2,250–2,010° F.). It has also been found that in a travelling grate stoker it requires 1 per cent. of the steam generated in the boiler to lower the link temperature by 30° C. (53° F.) with a caking coal, and 50° C. (90° F.) with a non-caking coal.

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CHAPTER 9

HEAT TRANSMISSION

THE process of heating involves three stages. Firstly, the heat must be generated by efficient combustion, as discussed in Chapters 6–8. Secondly, the heat so generated must be transmitted as efficiently as possible to the heat-absorbing surfaces. Thirdly, the heat must be conserved in the heating appliance so as to do useful work, and its transmission to those parts of the appliance from which it might become wastefully dissipated must be kept to a minimum. The second and third of these operations are discussed in this chapter.

Heat may be transferred in three different ways, *conduction*, *convection*, and *radiation*, which are here discussed in that order. All three depend upon a difference of temperature between the bodies emitting the heat and those receiving it.

CONDUCTION

The simplest form of heat conduction occurs in a solid, for example a boiler plate or a furnace wall. One surface may be hot and the other cooler. The quantity of heat conducted through the body in a given time is

- (a) directly proportional to the difference in temperature between the hot surface and the cold surface,
- (b) inversely proportional to the thickness of the plate or wall through which the heat is passing, and
- (c) directly proportional to the total area of the surface (normal to the direction of heat flow) of the plate or wall through which the heat is passing.

Furthermore every material has its individual capacity for conducting heat, characteristic of the material itself.

The familiar reference to good conductors such as metals, and bad conductors such as firebrick, lagging compounds and boiler scale, can be reduced to a form of expression suitable for use in heating problems, by stating the number of heat units (British thermal units—B.t.u.) that can be conducted in one hour through a slab of the material one square foot in section and one foot thick, when there is a difference in temperature of 1 degree F. between the hot face and the cold face. When the temperatures are steady, the conduction is referred to as taking place “in the steady state”; under these conditions the number of heat units conducted hourly is referred to as the *thermal conductivity* of the material. It is necessary to distinguish between the steady or uniform flow of heat and fluctuating flow, since in fluctuating flow heat may be given to, or taken from, the body of the slab. However, all the examples in this chapter deal with heat transfer under steady conditions.

CONDUCTION OF HEAT THROUGH WALLS

The law of conduction, which has been described in words above, can be expressed in the following manner for the case of heat flowing across a plate with parallel sides (Fig. 1), the direction of flow being at right angles to the sides of the plate.

q , the heat flow (in heat units per unit time) varies as $\frac{(t_1 - t_2)A}{L}$.

$$\text{Thus } q = \frac{k(t_1 - t_2)A}{L} \dots \dots \dots (1)$$

where t_1 is the temperature of the hot face

t_2 is the temperature of the cold face,
 L is the thickness of the wall,
 A is the area across which the heat is being conducted,
and k , the constant of proportionality, is characteristic of each material and is known as its *thermal conductivity*.

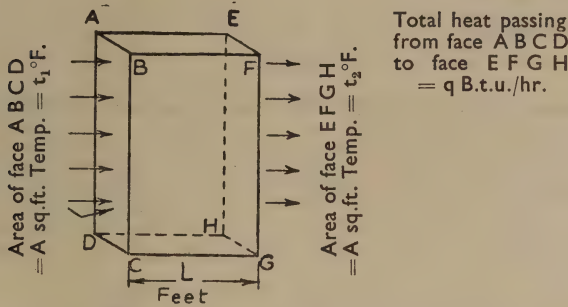


FIG. 1. Heat flow by conduction in a rectangular slab.

For the conduction of heat through unit area of cross section

$$\frac{q}{A} = \frac{k(t_1 - t_2)}{L} \dots \dots \dots (2)$$

Using British (foot-pound-hour) units throughout,

- q is expressed in B.t.u./hr.
- L is expressed in feet,
- t_1, t_2 , are expressed in Fahrenheit degrees,
- A , the area of the surface, is expressed in square feet, and
- k , the thermal conductivity is expressed as B.t.u. per sq. ft. hr. per deg. F. for one foot thickness, more generally written B.t.u./sq. ft. hr. deg. F./ft.

When it is more convenient to express the thickness of the wall “ L ” in inches, “ k ” is expressed as B.t.u./sq. ft. hr. deg. F./in.

The term $\frac{q}{A}$ is known as the heat transfer rate “ H ”, expressed as B.t.u./sq.ft.hr.,

and from this it will be seen that

$$H = k(t_1 - t_2)/L. \dots \dots \dots (3)$$

THERMAL CONDUCTIVITIES

The thermal conductivities of some substances commonly entering into industrial heat problems are shown in Table 1. Both values for k mentioned above are given in that table.

The table shows the marked difference in thermal conductivity between metals and non-metals. Thermal conductivity varies with temperature also, and may increase or decrease with rise of temperature. Thermal conductivities of metals are generally less at high temperatures than at lower temperatures, whereas those of most refractory materials are generally higher at the higher temperatures. Examples of these differences are given in the table.

When calculating the rate of heat transmission through a substance, the thermal conductivity to be used is the average over the relevant temperature range. For aluminium, the conductivities at 400° C. and 600° C. expressed as B.t.u./sq. ft. hr. deg. F./in. are 1,730 and 2,000 respectively ; thus the value 1,865 is used in calculations between these temperatures.

Some tables give values for thermal conductivity in c.g.s. units, e.g. cal./sq.cm.sec.deg.C./cm. Such values can be converted to B.t.u./sq.ft.hr.deg.F./in. and B.t.u./sq.ft.hr.deg.F./ft. by multiplying by 2,900 and 241.9 respectively. The factors for converting values in British units into c.g.s. units are 0.000344 and 0.00414 respectively.

HEAT TRANSMISSION

TABLE 1
THERMAL CONDUCTIVITY OF SOME COMMON MATERIALS

Material	Temp. ° C.	Thermal conductivity (a)	
		B.t.u./sq. ft. hr. deg. F./in.	B.t.u./sq. ft. hr. deg. F./ft.
Aluminium	0	1,400	117
	200	1,490	124
	400	1,730	144
	500	1,860	155
Copper	100-200	(b) 2,916	(b) 243
	100-370	(b) 2,700	(b) 225
	100-541	(b) 2,620	(b) 218
	100-837	(b) 2,500	(b) 208
Wrought iron	500	2,484	207
	18	418	35
	100	416	35-32
	400	314	26
Cast iron	500	276	23
	100	314	26
Steel, mild	100	311	26
	400	276	23
Nickel	600	258	21
	100	400	33
	300	366	31-31
	600	256	21
Monel metal	800	197	17
	1,200	168	14
	100	203	17
	400	244	20
Brass	100	711	59
	400	810	68
Firebrick (c)	300	7.3	0.61
	700	8.1	0.68
Magnesite brick (c) (86% MgO)	1,100	8.4	0.70
	500	24.9	1.9
	700	20.6	1.6
	1,100	17.4	1.1
Insulating bricks (c) (porous diatomaceous)	0-200	(b) 0.73	(b) 0.06
	0-400	(b) 0.81	(b) 0.07
	0-600	(b) 0.90	(b) 0.08
	0-800	(b) 1.02	(b) 0.09
Magnesia pipe covering	50	0.38	0.03
	100	0.41	0.03
	200	0.46	0.04
	400	0.64	0.05

(a) The dimensions are strictly $\frac{\text{B.t.u.}}{\text{ft. hr. deg. F.}}$ but are stated in the form given for clarity.

(b) Mean values for the temperature range given.

(c) Thermal properties of other refractory and insulating materials are given in Chapter 23.

Examples :

(a) *Rate of transfer of heat through a firebrick wall.*

Thickness of wall—6 in.

Hot face temperature—2,010°F. (approx. 1,100°C.).

Cold face temperature—1,130°F. (approx. 610°C.).

The average value of the conductivity of the firebrick over the temperature range 1,130° F. to 2,010° F. (approx. 610–1,100° C.) is known to be 8.2 B.t.u./sq. ft. hr. deg. F./in. Then, from Equation 3,

$$H = 8.2 \times \frac{(2,010 - 1,130)}{6} = 1,200 \text{ B.t.u./sq. ft. hr.}$$

(b) *To illustrate the effect of differences in conductivity.* Suppose that in a furnace of the muffle type the inner wall is to be maintained at 752° F. (440° C.) and that it is required to calculate what must be the temperature of the flue if the muffle wall is

(i) of cast iron 1 in. thick,

(ii) of firebrick $4\frac{1}{2}$ in. thick

when $H = 700$ B.t.u./sq. ft. hr.

Here the heat transfer rate through the wall is the same for the two cases, but the thermal conductivities of the materials are very different; they are taken as 300 for cast iron and 8 for firebrick.

$$\text{For cast iron, } 700 = 300 \times \frac{(t_1 - 752)}{1}$$

$$\text{hence } t_1 = 754.3^\circ \text{ F. (401.3}^\circ \text{ C.)}$$

$$\text{For firebrick, } 700 = 8 \times \frac{(t_1 - 752)}{4\frac{1}{2}}$$

$$\text{hence } t_1 = 1,146^\circ \text{ F. (619}^\circ \text{ C.)}$$

CONDUCTIVITY FORMULA FOR COMPOSITE WALLS

The standard conductivity formula requires modification when the wall is composed of more than one material. For example, if heat flows through a wall made up of three layers—of thicknesses L_1 , L_2 and L_3 —the temperature differences across the layers being ΔT_1 , ΔT_2 and ΔT_3 respectively (Fig. 2) and the conductivities k_1 , k_2 and k_3 respectively, the rate of heat transfer is derived as explained below.

Considering an area, A , of the wall, and using Equation 2,

$$\text{in layer 1. } q/A = k_1 \Delta T_1 / L_1 \quad \therefore \Delta T_1 = q L_1 / k_1 A$$

$$,, \quad 2. \quad q/A = k_2 \Delta T_2 / L_2 \quad \therefore \Delta T_2 = q L_2 / k_2 A$$

$$,, \quad 3. \quad q/A = k_3 \Delta T_3 / L_3 \quad \therefore \Delta T_3 = q L_3 / k_3 A$$

Now the overall temperature difference

$$\Delta T_0 = \Delta T_1 + \Delta T_2 + \Delta T_3$$

$$\therefore \Delta T_0 = (t_1 - t_2) = q/A (L_1/k_1 + L_2/k_2 + L_3/k_3)$$

$$\text{or } q/A = H = \frac{t_1 - t_2}{L_1/k_1 + L_2/k_2 + L_3/k_3} \text{ B.t.u./sq. ft. hr.} \quad (4)$$

Example :

If a wall consists of 9 in. of brickwork ($k_1 = 8.1$) backed by 3 in. of insulating brick ($k_2 = 0.8$), the inside surface temperature, t_1 , being 2,000° F., and the outer surface temperature, t_2 , 300° F., the heat that will pass through is derived as follows:

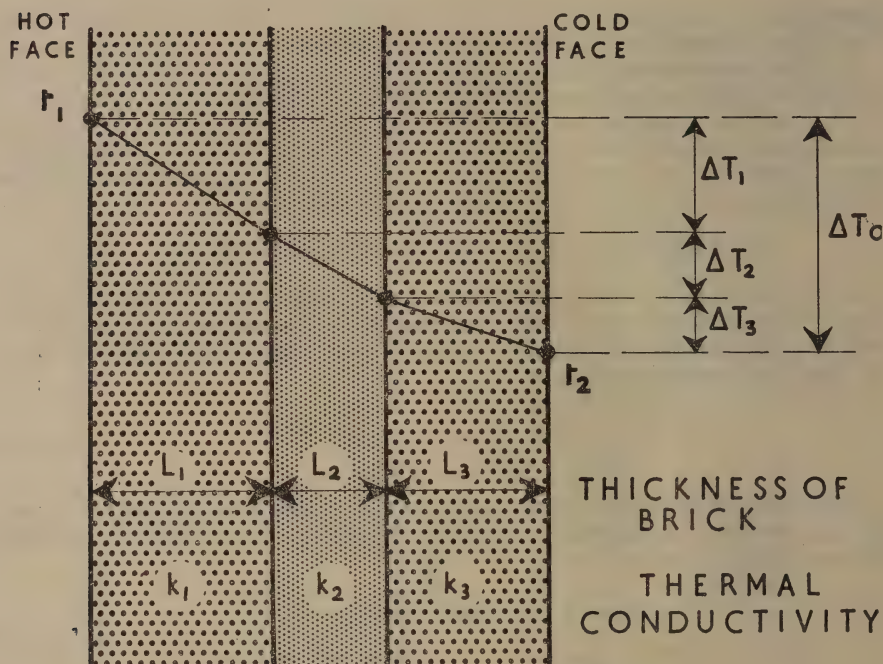


FIG. 2. Conduction through a composite wall.

$$H = \frac{2,000 - 300}{9/8 \cdot 1 + 3/0 \cdot 8} = 350 \text{ B.t.u./sq. ft. hr.}$$

A further example applies to the water side of a boiler on which a layer of scale may have formed. Scale (like firebrick) has a thermal conductivity of 12–18 B.t.u./sq. ft. hr. deg. F./in., though some scales can have a much lower conductivity. If it is accepted that the safe maximum (continuous) temperature for boiler tubes is 900° F., it is possible to estimate the thickness of scale that might entail the risk of the plates becoming dangerously overheated (because of the temperature difference that would exist across the scale). The following calculation illustrates this:

Example :

In modern boilers, heat input rates are of the order of 70,000–100,000 B.t.u./sq.ft.hr. If the pressure in a boiler is 100 lb./sq.in. —corresponding to a water temperature of 328° F.—the standard conductivity formula gives the equation

$$70,000 = \frac{18 (900 - 328)}{L}, \text{ hence } L = \frac{1}{8} \text{ inch (approx.)}$$

Thus a scale only about $\frac{1}{8}$ of an inch thick may set up a dangerous condition in the boiler. The scale also lowers thermal efficiency, the effect being a loss of $1\frac{1}{2}$ to 6 per cent., according to how much of the total boiler heating surface is coated with scale.

HEAT TRANSFER COEFFICIENT

A distinction must be drawn between *thermal conductivity* and the concept of *conductance*. The thermal conductance, or *heat transfer coefficient*, h , of a solid is the number of heat units passing in unit time through unit area of the

solid (the area concerned being measured at right angles to the direction of flow), when the temperature difference between the hot surface and the cooler surface of the solid is one degree (Fahrenheit or Centigrade).

For solids, the equation giving the heat transfer coefficient is

$$h = \frac{k}{L}$$

When k , the thermal conductivity of the solid, is expressed as B.t.u./sq. ft. hr. deg. F./ft. and L , the thickness of the solid, is expressed in feet, then h is expressed as B.t.u./sq. ft. hr. deg. F.

By writing $\frac{L_1}{k_1} = \frac{1}{h_1}$, $\frac{L_2}{k_2} = \frac{1}{h_2}$, and $\frac{L_3}{k_3} = \frac{1}{h_3}$ in Equation 4, the rate of heat transfer (H) through the wall may be written as

$$H = \frac{(t_1 - t_2)}{\frac{1}{h_1} + \frac{1}{h_2} + \frac{1}{h_3}} \quad \dots \dots \dots (5)$$

CONDUCTION THROUGH PIPE WALLS

Although the formulae for conductivity through a flat surface, given on page 151 are approximately correct for a curved surface of large diameter, provided the thickness of the wall is small compared with the diameter, they are incorrect when the diameter is small. For calculations of the flow of heat through pipe coverings other formulae, based on the same general principles, must be used.

If the outside diameter of a pipe is d_1 and the diameter of the outer surface of the pipe covering is d_2 it can be shown that the heat flow is given by the equation :

$$q = \frac{2\pi k}{2.3 \log \frac{d_2}{d_1}} (t_1 - t_2) \text{ B.t.u./hr. for each foot run of pipe} \dots (6)$$

where t_1 and t_2 are the temperatures at diameters d_1 and d_2 respectively and k is the conductivity of the covering expressed as B.t.u./sq. ft. hr. deg. F./ft.

This is perhaps the most useful form for practical purposes, but if the loss of heat per unit surface area of the pipe is required, it is given by:

$$H = \frac{k}{2.3r \log \frac{d_2}{d_1}} (t_1 - t_2) \text{ B.t.u./sq. ft. hr.} \dots \dots \dots (7)$$

When k is expressed as B.t.u./sq. ft. hr. deg. F./ft., r , the distance from the pipe axis, must be expressed in feet; when k is B.t.u./sq. ft. hr. deg. F./in., r must be expressed in inches. When $r = \frac{1}{2}d_1$ Equ'n. 7 gives the heat loss per unit area of the metal pipe, and when $r = \frac{1}{2}d_2$, the heat loss is based on the area of the external covering.

Example:

If a 6-inch steam pipe is covered by $2\frac{1}{2}$ inches of magnesia, experiment shows that the surface temperature of the magnesia in reasonably still air is 120°F. , when the pipe is conveying steam at 500°F. (see Fig. 3).

The thermal conductivity of the magnesia covering may be taken as 0.35 over this temperature range. The heat lost per foot run is then calculated:

$$q = \frac{2\pi \times 0.35 (500 - 120)}{2.3 \log (11/6)} = 1,400 \text{ B.t.u. per hour}$$

The heat lost per square foot of surface area of the metal pipe is given by:

$$H = \frac{0.35 (500 - 120)}{2.3 \times 0.25 \log (11/6)} = 890 \text{ B.t.u. per hour.}$$

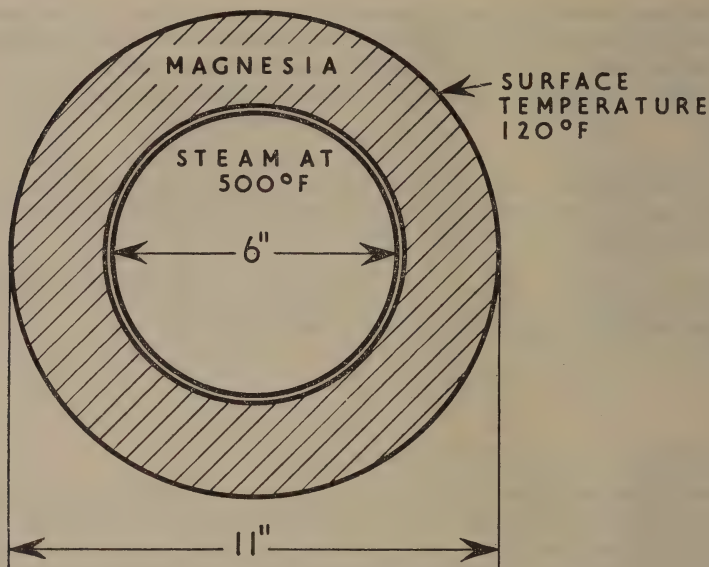


FIG. 3. Cross-section of an insulated steam pipe

CONVECTION

Convection is the transfer of heat given to or received from fluids (liquids and gases) and the further process of conveying that heat to other surroundings. The most familiar example, *natural convection*, is that whereby the upward movement of the fluid is due to the buoyancy resulting from its expansion under the influence of heat, which reduces the density relative to that of any surrounding fluid. Examples are: hot gases rising from a bonfire, hot flue gases passing up a chimney, hot water from a domestic boiler rising into the hot water storage tank. When the motion of the fluid which is transferring heat is brought about mechanically, e.g. by a pump, the mode of transfer is called *forced convection*.

Convection transfer is bound up ultimately with the mechanism of flow of fluids (discussed in detail in Chapter 10) and is an important factor in the heating of waste-heat fire-tube boilers, and in any form of heat exchanger in which a fluid flows over the heat-exchanging surface, for example in superheaters and economisers, and air heaters. The velocity of flow is of much significance in these conditions.

NATURAL CONVECTION IN AIR

The transfer of heat by natural convection is governed by the area of the surface, the shape and position of the surface and the temperature difference between the surface and the air. A useful empirical expression for the rate of heat transfer, H , is

$$H = C (t_1 - t_2)^{1.25} \text{ B.t.u./sq. ft. hr.} \quad (8)$$

where t_1 is the temperature of the surface, t_2 of the gas or air, and C is a constant depending on the shape and position of the surface.

The value of C as determined by experiment is as follows:

$C = 0.39$ for a plane horizontal surface facing up and hotter than the gas; or facing down and colder than the gas.

$C=0.3$ for plane vertical surfaces and for large bodies of irregular shape but without re-entrant angles.

$C=0.2$ for horizontal surfaces facing downwards and hotter than the gas.

For large horizontal cylinders (and this applies to pipes) over 6 inches diameter $C=0.35$. As the cylinder diameter decreases (e.g. with small pipes) the value of C increases rapidly, so that for a wire of 0.01 inch diameter $C=3.5$.

Some idea of the magnitude of natural convection effects can be seen from Fig. 4.

As a simple example of the use of Equation 8, consider a bare hot water tank filled with hot water at 180° F. in a workshop which has an air temperature of 70° F.

The tank is supported on four columns so that its base is exposed. It measures 20 feet × 14 feet wide, and is 10 feet high. It is connected to an apparatus where the water is used, by a pipe 8 inches in diameter and 15 feet long. It is required to calculate the loss of heat per hour by convection.

					<i>Sq. ft.</i>
Area of connecting pipe	..	..	..	..	31.4
Area of top of the tank	..	..	..	..	280
Area of bottom of the tank	..	..	..	..	280
Area of sides of the tank	..	..	..	..	680

Heat loss from connecting pipe = $0.35 \times 31.4 \times (180-70)^{1.25}$
= 3,900 B.t.u. per hour.

Heat loss from top of tank = $0.39 \times 280 \times (180-70)^{1.25}$
= 40,000 B.t.u. per hour.

Heat loss from bottom of tank = $0.2 \times 280 \times (180-70)^{1.25}$
= 20,000 B.t.u. per hour.

Heat loss from sides of tank = $0.3 \times 680 \times (180-70)^{1.25}$
= 72,600 B.t.u. per hour.

$H = 3,900 + 40,000 + 20,000 + 72,600 = 136,500$ B.t.u. per hour.

In addition to this there is loss by radiation which will be dealt with in a later section. Since the tank is unlagged it has been assumed in the foregoing example that the surfaces of the tank are at the same temperature as that of the water. The loss of heat can be reduced if the temperature drop (180-70)° F. can be decreased. If the tank and pipe are lagged, the surface temperature should be reducible at least to 90° F. The loss of heat by convection will then be reduced to 16,200 B.t.u. per hour—a striking commentary on the value of adequate insulation.

FORCED CONVECTION—FLOW IN PIPES

Reynolds' Number

In his classical experiments on the subject, Osborne Reynolds showed the difference between streamline or laminar flow and turbulent flow. With the transition from streamline flow to turbulent motion, fluid friction increased instantaneously and the law governing the pressure drop through the tube changed.

Reynolds showed also that certain relationships existed between the fluid friction and the composite effect of velocity (V), depth of the fluid stream (D), density of the fluid (ρ), and its viscosity (η), which could be grouped together to give a criterion known as *Reynolds' Number* (Re). A fuller account of this subject is given in Chapter 10; it is sufficient here to state that

$Re = \frac{VD\rho}{\eta}$ (9)

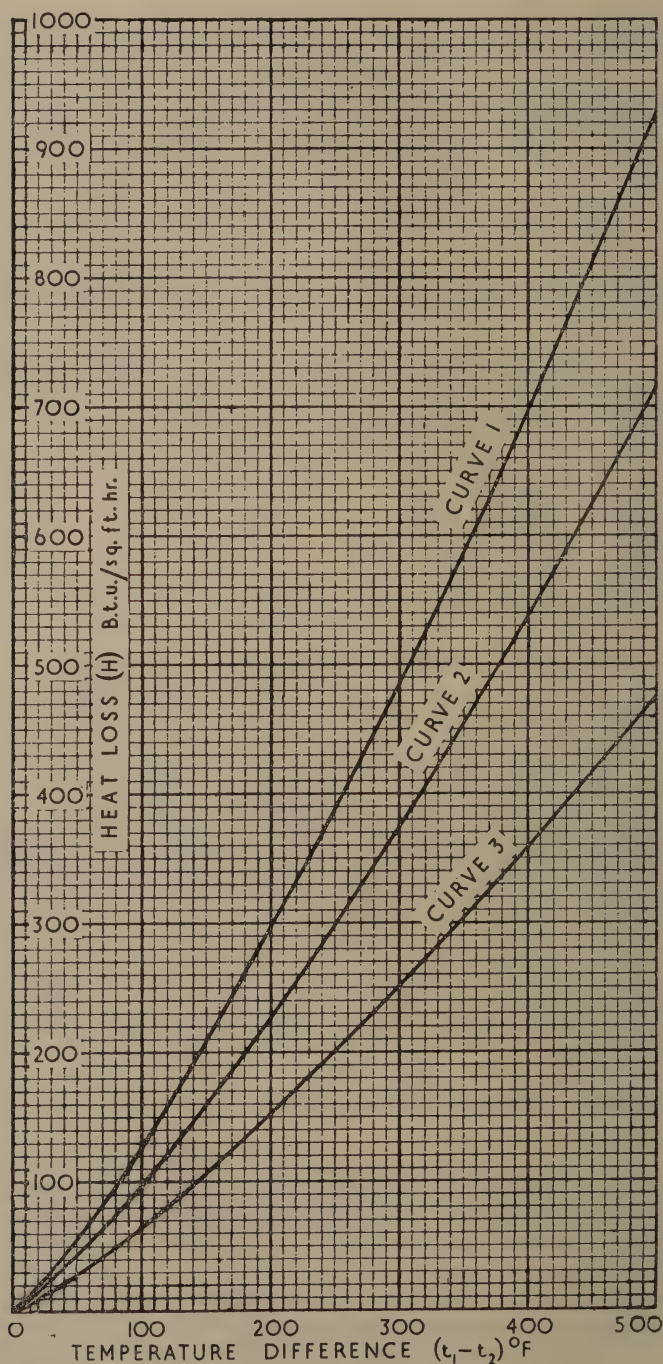


FIG. 4. Heat transfer by natural convection in still air.

CURVE 1: Horizontal hot surface facing upwards, $C = 0.39$.

„ 2: Vertical surface or large irregular shape without re-entrant parts, $C = 0.3$.

„ 3: Horizontal hot surface facing downwards, $C = 0.2$.

It should be emphasised that ρ and η are respectively the fluid density and the viscosity at the temperature and pressure ruling at the time. The units chosen to represent the four variables V , D , ρ and η *must be consistent*, i.e. all in British units or all in c.g.s. units. This is because Re is simply a number or a ratio; it is non-dimensional.

- For example, if V is given in ft./sec.
- D is given in ft.
- and ρ is given in lb./cu. ft.
- then η must be expressed as lb./sec. ft.

The change from streamline flow to turbulent flow is associated with a Re value within the range 1,300–2,100. (But see further in Chapter 10). It has been shown that the transfer of heat from moving fluids is associated with the characteristics of flow and that heat transfer and resistance to fluid flow are closely related.

The velocity distribution in the streams of fluid flowing in two pipes is the same if the respective Reynolds' Numbers are the same. Similarly, the temperature distribution in the streams is the same if the expression $V.D/a$ —where 'a' is the *thermal diffusivity*—is the same for both, thermal diffusivity being conductivity divided by the product of the specific heat (on a mass basis) and the density.

Study of these groups has shown that for specific applications they bear a simple relation to each other. Thus Nusselt developed the following relationship :

$$\frac{hD}{k} = f \left(\frac{VD}{a} \right) \dots \dots \dots (10)$$

- where k =thermal conductivity.
- h =heat transfer coefficient
- D =width of stream, i.e. internal diameter of the pipe.

The group $\frac{hD}{k}$ (known as the Nusselt Number, Nu) is, like the Reynolds' Number, dimensionless if consistent units are used. Nusselt found that for heat transfer from a fluid flowing in a tube the surface conductance, or heat transfer coefficient, h , is directly related to the 0.786th power of the velocity.

In practice this is expressed by the equation

$$h = C.V^{0.8} \dots \dots \dots (11)$$

where C is a composite factor.

It can be shown by the development of the above equations that the heat transfer coefficient is derivable from

$$h = \frac{k}{D} C' \left(\frac{VD}{a} \right)^{0.8} \dots \dots \dots (12)$$

in which C' is a general constant determined by the specific conditions. Thus for forced turbulent flow of gas in pipes

$$h = 15.9 \frac{k_{wall}}{D^{0.2}} \left(\frac{VC_p}{k} \right)^{0.8} \text{ B.t.u./sq. ft. hr. deg. F. } \dots (13)$$

Certain transformations have been made and the symbols are

- k_{wall} =thermal conductivity of the gas at the temperature of the pipe wall; B.t.u./sq. ft. hr. deg. F./ft.
- k =thermal conductivity of the gas at its mean temperature; B.t.u./sq. ft. hr. deg. F./ft.

C_p =specific heat of the gas under the conditions of flow;
B.t.u/cu. ft. deg. F.

V =velocity of the gas flow; feet per second,

D =internal diameter of the pipe; feet.

Generally the derivation of 'h' by means of the Reynolds' criterion is complex and beyond the aims of this chapter, which are to provide a basis for study and to indicate the sources of the most useful formulae.

Applying, in Equation 13, the usual values for thermal conductivity, etc., for chimney gases and air, the convective heat transfer coefficient for turbulent flow in long smooth pipes is given by

$$h = \frac{0.32V^{0.8}}{\sqrt[4]{D}} \text{B.t.u./sq. ft. hr. deg. F.} \quad (14)$$

where V =fluid velocity in feet per second calculated to S.T.P.

D =internal diameter of the duct; feet.

For ducts other than circular, the equivalent diameter is given by (area of cross-section $\times 4$) \div (perimeter in contact with the fluid).

The above formulae all give the heat transfer coefficient, h , from which the rate of heat transfer, H , may be found as follows:

$$H=h (t_1-t_2)\text{B.t.u./sq. ft. hr.} \quad (15)$$

if h is expressed in B.t.u./sq. ft. hr. deg. F.

and temperatures are expressed in deg. F.

Thus the rate of heat transfer depends directly upon the difference of temperature between the hot and cold elements of the heat-exchanging surface, and not upon the $5/4$ power of the temperature difference as in the case of natural convection.

The heat transfer coefficient h is analogous to k , the thermal conductivity. The parallel is, however, far from being exact, for unlike k , which is a characteristic of the material and of the temperature, the value of h depends also upon the linear velocity of the stream, the size of the body, and the physical properties of the fluid. Equation 15 is applicable to a wide range of conditions, the value of h naturally varying with circumstances; some examples are discussed below in general terms.

For a more detailed treatment of the subject of convective heat transfer the reader is referred to the bibliography¹⁻³ at the end of the chapter.

AIR FLOWING ACROSS A SINGLE TUBE

Fig. 5 shows the values found for h for tubes of various sizes in air. If the turbulence of the gas stream is artificially increased these values may be increased by up to 50 per cent. Increased turbulence, however, causes increased resistance to the flow of the fluid. Increased draught is thus needed; consequently this method of increasing the heat flow must be used with caution. A Galloway tube is an example of this arrangement.

A simple equation⁴ for the highly turbulent flow of air against a single tube is:

$$h = 0.76 \frac{V_0^{0.56}}{D_0^{0.44}} \text{B.t.u./sq. ft. hr. deg. F.} \quad (16)$$

where V_0 = air velocity in feet per second, calculated to S.T.P.,
 D_0 = external diameter of the tube, in feet.

For undisturbed flow the constant becomes 0.70.

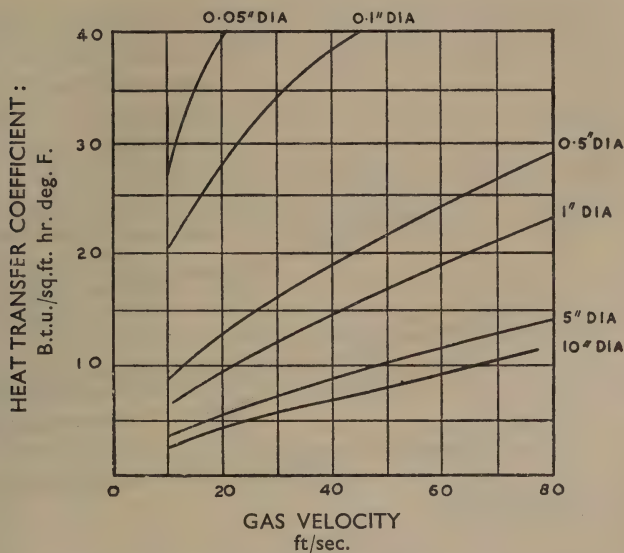


FIG. 5. Heat lost from cylinders, by forced convection, to air flowing at right angles to the cylinder.

(Based on "The Calculation of Heat Transmission," by M. Fishenden and O. A. Saunders. H.M.S.O.)

AIR FLOWING ALONG, OUTSIDE A SINGLE TUBE

The mean value of *h* for any given conditions is about half that for the transverse stream (Fig. 5), but can be doubled by creating artificial turbulence.

GASES FLOWING THROUGH A SINGLE TUBE

The circular flues of a shell boiler, a main carrying hot producer gas, some forms of air heater, or any other arrangement in which the gas being heated flows through a tube, are examples of this class of problem.

Here it is found that

$$h = Bv^{0.8} \text{ B.t.u./sq. ft. hr. deg. F. (17)}$$

where *v* is velocity; ft./hr.

B is a factor, the value of which is given in Fig. 6.

Another treatment of this arrangement on more general lines is that indicated by Equation 14.

HEAT TRANSFER FROM SUPERHEATED STEAM AND CONDENSING VAPOURS

Fundamental investigations of heat transmission by convection have produced equations for practical use applicable to all fluids, but superheated steam and condensing and boiling liquids introduce special conditions. Some authorities doubt whether the equations for superheated steam are satisfactory and further investigation is needed. The following is a satisfactory general equation for superheated steam in pipes:

$$h = \left(0.432 + 0.151 \frac{t}{1,000} \right) \frac{V_0^{0.79}}{D^{0.16} L^{0.05}} \text{ B.t.u./sq. ft. hr. deg. F. . . (18)}$$

- where *t* = steam temperature ; °F.
- V*₀ = steam velocity referred to S.T.P.; ft./sec.
- L* = length of pipe; ft.
- D* = inside diameter of pipe; ft.

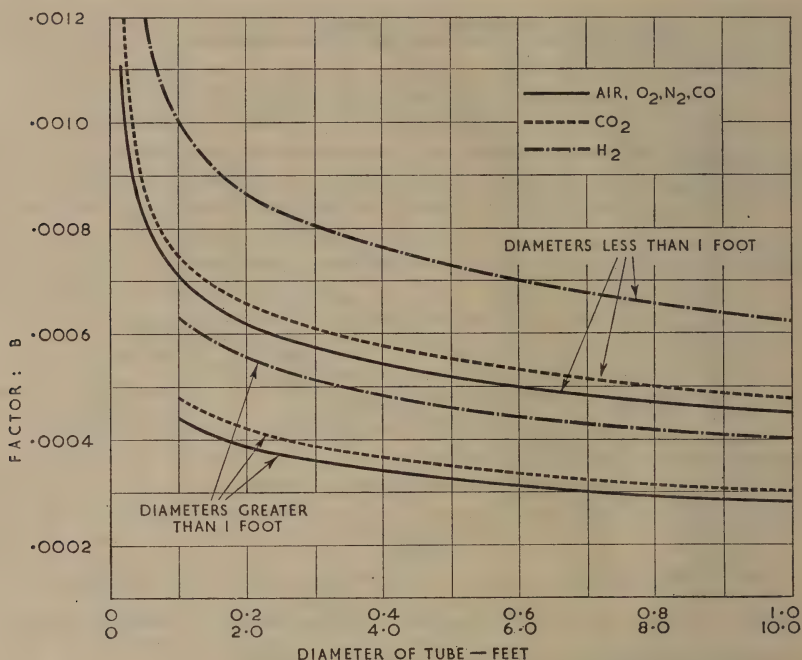


FIG. 6. Heat transfer coefficients for forced convection of gases through tubes of different diameters.

(From "The Calculation of Heat Transmission," Fishenden and Saunders. H.M.S.O.)

The inclusion of a term, L , the length of the pipe, is due to the reduction in turbulence as the length of the pipe increases.

Heat transfer from saturated vapours differs fundamentally from heat transfer by convection from gases. As soon as a saturated vapour touches a surface colder than itself condensation occurs, and the latent heat of condensation is given up to the cooling surface. At the same time, a film of the condensed liquid is formed on the cooling surface and further heat transfer takes place through that film. Since liquids are generally bad conductors the presence of the film is of significance.

For this reason, it is found that the character of the heat transfer in horizontal positions is different from that in vertical positions. Thus, the height of a vertical condensing column, the viscosity of the liquid and the roughness of the surface all appreciably affect the resultant heat transfer.

The heat transfer coefficient of condensing saturated steam is given approximately for minimum values by the following:

$$h = \frac{A+B(t_s+t_w)}{\sqrt[4]{L}(t_s-t_w)} \text{ B.t.u./sq. ft. hr. deg. F.} \quad (19)$$

where

t_s = steam temperature; °F.,

t_w = wall temperature; °F.,

L = length of vertical pipe or diameter of horizontal pipe.

and A and B have the values here shown

	A	B
vertical pipe	1,590	4.07
horizontal pipe	1,225	3.15

Alternatively, alignment charts by which problems falling into this class can be solved are given¹ in "Heat Transmission" (McAdams). p. 337.

DROPSWISE CONDENSATION ON A METAL SURFACE

When steam condenses on to a cooled metal surface that has not been specially prepared, there are generally patches of surface covered by a continuous film and intermediate regions bearing drops of condensate. By appropriate treatment, either of two opposing extreme conditions may be obtained:—

- (1) *Filmwise*—the condensate is distributed as a continuous film over the surface.
- (2) *Drops wise*—the condensate forms separate droplets on the surface.

It is of practical importance to discover means to obtain prolonged dropwise condensation because the heat transfer rate is very much greater with dropwise than with filmwise condensation. Table 2 gives a *comparison* of heat transfer coefficients obtained for dropwise and filmwise condensation of steam on a copper surface.

TABLE 2. COMPARISON OF HEAT TRANSFER COEFFICIENTS
(Orders of magnitude only)

Pure copper plate—0.123 in. thick—surface vertical—one side kept cool by water flowing at 10 ft./sec.

Type of condensation	Overall heat transfer coefficient, U (B.t.u./sq. ft. hr. deg. F.)	Steam-side heat transfer coefficient (B.t.u./sq. ft. hr. deg. F.)
Dropwise ..	2,000–2,500	20,000–25,000
Filmwise ..	700–1,000	1,500 – 2,500

The table demonstrates that although the steam side heat transfer coefficient is more than ten times as much with dropwise as filmwise condensation, the overall heat transfer has in this case been increased to just under three times as much. This shows that the heat transfer is being limited on the water side and before the full benefits of dropwise condensation on the steam side can be realised, the conditions on the water side must be such that heat transfer will not be restricted. Thus with existing designs the greatest increases in heat transfer due to rendering the metal surface unwettable will be realised on evaporators and similar heat exchangers rather than those like surface condensers where the water side heat transfer is limited.

Condensate forms a continuous film (filmwise condensation) only if the surface on to which the vapour is to condense is completely "wetable"; it forms drops (dropwise condensation) when the surface is "unwettable". Neither of these extremes is obtainable in practice. Maximum wettability is obtained by making the surface chemically clean, and keeping it so. Maximum unwettability is obtained by treating the (metal) surface with one or other of a range of chemical "promoters".

Research on dropwise condensation and promoters is still in progress; numerous organic compounds have been synthesized at Queen Mary College (University of London) which have successfully promoted dropwise condensation.⁵ At present these promoters have been applied only to copper, or metal containing copper. If the promoter is to have a lasting effect it must be a substance with a high affinity for the metal surface so that a chemical bond is made. If promoters such as varnishes, which have a physical bond, were required to have a lasting effect they would be so thick that the resistance to heat flow would be increased rather than reduced. Promoters that are

chemically bonded can be injected into the heat exchangers in small quantities at intervals and their cost would be negligible compared with the benefits realised.

HEAT TRANSFER AND PRESSURE DROP IN FLOW ACROSS BANKS OF TUBES

In discussing the contribution made by Osborne Reynolds to our knowledge of fluid flow, the importance of the resistance to flow introduced by fluid friction was indicated. In practical design, heat transfer and the resistance to flow through the appliance must always be considered together. There is an economic balance for some optimum value of resistance to fluid flow and the area of the heating surface because the cost of equipment and the cost of power tend in opposite directions.

In banks of tubes, occurring in so many forms of heating appliances and exchangers, the heat transfer coefficient, h , is given in all cases of forced convection by a relation between the Nusselt Number and the Reynolds' Number, which depends upon the geometrical arrangement of the tubes.

The relation fitting the most reliable experimental data⁴ is

$$\frac{hD_o}{k} = 0.29 C_H \left(\frac{VD_o\rho}{\eta} \right)^{0.61} \quad \dots \dots \dots (20)$$

h = heat transfer coefficient; B.t.u./sq. ft. hr. deg. F.

D_o = external diameter of pipe; feet,

k = thermal conductivity of fluid; B.t.u./sq. ft. hr. deg. F./ft.

$\frac{VD_o\rho}{\eta}$ = Reynolds' Number,

and the constant C_H depends upon the tube arrangement. The velocity V is measured at the narrowest restriction. This may occur between adjacent tubes in line, or between two diagonally opposed tubes.

Frictional resistance to flow in pipes is given by the well-known D'Arcy formula (also known as the Fanning Equation), which is discussed in detail in Chapter 10. According to this expression,

if Δp = pressure drop; lb./sq. ft.

D = pipe diameter; ft.

f = coefficient of friction

w = specific weight; lb./cu. ft.

L = length of pipe; ft.

V = velocity; ft./sec.

$$\Delta p = 1.295 \times 10^{-3} \frac{fLwV^2}{D} \quad \dots \dots \dots (21)$$

For flow across tube banks this can be resolved into

$$\Delta p = C_F n_w V^2$$

where C_F = coefficient of discharge depending on the tube arrangement,

n = number of rows of tubes.

Values of the constants C_H and C_F for various arrangements of tube banks, both in line and staggered are to be found in the paper by Lander (*loc. cit.*). The magnitude of the heat transfer is proportional to the corresponding value of the coefficient C_H in both in-line and staggered arrangements. For "in-line" arrangements with values of the Reynolds' number above 20,000 C_H becomes unity for all kinds of spacings, from which it follows that the heat transfer is determined by the velocity. The mean value of the heat transfer at wide spacings in line is about 38 per cent. below that for a single tube, due to the shielding effect of one tube on another. For staggered formations the pressure drop appears to be quite independent of the longitudinal space, but rises as the lateral spacing is decreased.

In general, a heat exchanger may become more economical as the pipe diameter is decreased. The installation cost decreases approximately with the fourth root of the pipe diameter, but practical conditions limit the reduction of cross section.

Another useful equation for heat transfer by convection from air to rows of pipes evenly arranged or in staggered bundles has the following general form:

h = (C.V_o^x) / D^y (22)

V_o is measured at S.T.P. as in Equation 16.
The values for the various groupings are given in Table 3. They are valid for air at any temperature and pressure, and are approximately valid for flue gases.

TABLE 3

Arrangement of pipe bundles		Even rows	Staggered rows
Values of indices	x	0.654	0.69
	y	0.346	0.31
No. of rows		C	C
2		0.615	0.70
3		0.635	0.79
4		0.65	0.86
5		0.66	0.91

The Use of Fins

In air heaters, and other plant, the heat transfer by forced convection is increased by adding fins or other projections to increase the effective surface area of the tubes. The heat transfer to fins is actually less than the heat transfer to the bare tube, but in view of the increased exposed surface, the overall heat transfer referred to the bare tube surface is increased. There is a limit to the useful height of the fins and their spacing. The larger and more numerous the fins the greater will be the heat transfer for a given base area; but increase in height causes a reduction in the mean temperature of the exposed surface and if the fins are too close the flow of air between them is impeded. The fins must be of sufficient thickness to conduct the heat to or from the tube wall without too great a temperature gradient.

HEAT TRANSFER FROM GASES TO WALLS

In forced convection in a plane wall, as distinct from natural convection, heat transfer has been found experimentally to depend not only upon whether the plate or wall is vertical or horizontal, but also on the character, particularly the roughness, of its surface. Data based on experimental work are as follows (Table 4).

TABLE 4
FORCED CONVECTION OVER PLANE WALLS
(Values of h in B.t.u./sq. ft. hr. deg. F.)

For velocities smaller than 16.5 ft./sec.	For velocities larger than 16.5 ft./sec.
0.98 + 0.20V, for a smooth surface	0.50V ^{0.78}
1.02 + 0.20V, for a rolled surface	0.50V ^{0.78}
1.09 + 0.22V, for a rough surface	0.52V ^{0.78}

The air velocity V is here referred to a basis of 70°F . If the temperature varies much from 70°F . the correction should be applied to bring the corresponding value of V to 70°F . Thus if the temperature is 200°F ., and the actual velocity 20 feet per second, the corrected value of V becomes

$$V = 20 \times \frac{460 + 70}{460 + 200} \text{ i.e. } 16.05 \text{ ft./sec.}$$

For surfaces greater than $1\frac{1}{2}$ sq. ft. and several feet in length h becomes decreased by as much as 40 per cent.

CONVECTION IN LIQUIDS

The layer of fluid in contact with a surface is virtually stationary; the next layer flows over this stagnant layer with imperceptible velocity, and so on, each succeeding layer moving with a higher speed.

The temperature drop through the stagnant layer is illustrated in Fig. 17. The significance of velocity in influencing the thickness of this non-conducting stationary layer or film will be readily apparent. The heat transfer coefficient is, for this reason, often known as the *film coefficient*. It is not surprising to find that for water flowing slowly in pipes the coefficient has a remarkably low value because the film is thick. In practice the coefficient for bodies in contact with water has values of the order of 40–200 according to the opportunity for the development of convection currents.

The correlation of experimental results on the basis of similarity transfer by forced convection for liquids flowing in tubes in turbulent motion has been shown by Fishenden and Saunders (*loc. cit.*, p. 186) to be

$$\frac{hD}{k} \left(\frac{cv}{k} \right)^{0.5} = 0.03 \left(\frac{VcD}{k} \right)^{0.8} \quad \dots \dots \dots (23)$$

where h =heat transfer coefficient; B.t.u./sq. ft. hr. deg. F.

D =diameter; ft.

k =thermal conductivity; B.t.u./sq. ft. hr. deg. F./ft.

c =specific heat; B.t.u./cu. ft. deg. F.

v =kinematic viscosity; sq. ft./sec.= η/ρ (see Chapter 10).

V =linear velocity; feet per second.

A simplified equation for the heat transfer coefficient of water at temperature t_w and flowing in pipes at a velocity of V ft. per second, based on a density of 62.3 lb./cu. ft. is

$$h = 150 (1 + 0.011 t_w) V^{0.8} / d^{0.2} \quad \dots \dots \dots (24)$$

where d =internal diameter of pipe, in inches and t_w , is $^{\circ}\text{F}$.

Fluid flow resulting from the boiling of the liquid at a heated surface must be distinguished from free convection since the ebullition introduces a measure of forced convection. The heat transfer coefficient for the boiling of water is of the order of 1,000–4,000 B.t.u./sq. ft. hr. deg. F., according to the intensity of boiling and the condition of water circulation. The aggregation of steam bubbles over an intensely heated area resulting in overheating owing to the insulating effect of the layer of gas bubbles is a recognised occurrence in regions of poor circulation. The fact that the heat transfer is somewhat greater for vertical than for horizontal surfaces is thus also to be expected. It has been established that the more viscous the liquid the lower is the heat transfer coefficient under conditions of ebullition.

LIQUID CONVECTION CURRENTS—BOILER CIRCULATION

Since water is a very poor conductor of heat, the absorption of the heat from the fire to the water side of a boiler must be brought about by currents

within the water. Experiments tend to prove that in comparatively stagnant water the water film next to the heated metal is heated by conduction, and subsequently breaks up into numerous small steam bubbles. Unless removed by rising through the liquid or by the flow of water over the surface to which they are attached, these form a heat-resisting blanket and reduce the flow of heat to the water. This effect may be observed in boilers having water "legs" or regions of poor circulation, the aggregation of steam bubbles over an intensely heated area resulting in overheating and possibly deformation of the plate. Water circulation is therefore of vital importance for even moderate rates of heat transmission.

Steam bubbles tend to rise, and since more are evolved in the region of the greatest heat transmission, the heating surface must be designed with free and adequate circulation on the water side. In a fire-tube boiler, for instance, the greatest evaporation takes place over the furnace. The water space above the furnace, therefore, should be clear of obstructions, and when tube nests are provided the tubes must be as widely spaced as possible.

In practice it is usual to provide suitable "lanes" between tube nests, through which the ascending hot water and steam bubbles flow once circulation has become established. An upward-moving current implies the existence of a downward flow to replace the water displaced; similar provision must be made for this. In Lancashire boilers the colder water may flow down the space between the flues and shell; in horizontal multitubular boilers a space of at least 3 inches must be left for this purpose between the outer tube peripheries and the boiler shell.

Lack of adequate circulation lanes in shell boilers causes erratic and violent ebullition, and when regions of the water space do not participate in the general circulation, heavy thermal stresses may be set up in the adjacent metal parts. This sometimes occurs in badly-designed boilers of the internally-fired type.

In water-tube boilers the conditions necessary for good circulation on the water side are the same, but their achievement in practice is complicated by the high rates of heat transmission possible in the water-tube boiler. Natural circulation results from the difference between the density of the water in the downcomer tubes and that of the mixture of steam and water in the risers. Tube surfaces are, accordingly, disposed to ensure that the riser tubes are more directly heated by the combustion gases, the downcomers being located in zones of lower gas temperature. In many modern designs the downcomers are, in fact, entirely external to the boiler heating surfaces. (See Chapter 14.)

Difficulty is sometimes experienced in arranging for an adequate flow of water to all the boiler tubes, the higher rate of flow in the tubes nearest the fire tending to starve the tubes at the cooler end of the boiler heating surface. Conditions may also arise in intermediate tubes which lead to a temporary stoppage or even a reversal of flow at low boiler loads.

Design is further complicated by the modern use of high feed water temperature and by the incorporation of furnace water walls in the circulation system. The practical implications of these factors are further referred to in Chapter 14.

OVERALL HEAT TRANSFER COEFFICIENT

The heat transmission, q , through a simple plane wall, e.g. in a boiler, separating two fluids, g and w , (see Fig. 7), can be obtained from the equation:

$$q = \frac{A(t_g - t_w)}{\frac{1}{h_g} + \frac{L}{k} + \frac{1}{h_w}} \text{ B.t.u./hr.} \quad (25)$$

where

A = area of heating surface ; sq. ft.

t_w = temperature of cold fluid (e.g. the water in the boiler) ; ° F.

t_g = temperature of hot fluid (e.g. hot gas in a boiler furnace) ; ° F.

h_g = heat transfer coefficient of hot fluid ; B.t.u./sq. ft. hr. deg. F.

h_w = heat transfer coefficient of cold fluid ; B.t.u./sq. ft. hr. deg. F.

L = thickness of wall ; feet.

k = thermal conductivity of the wall ; B.t.u./sq. ft. hr. deg. F./ft.

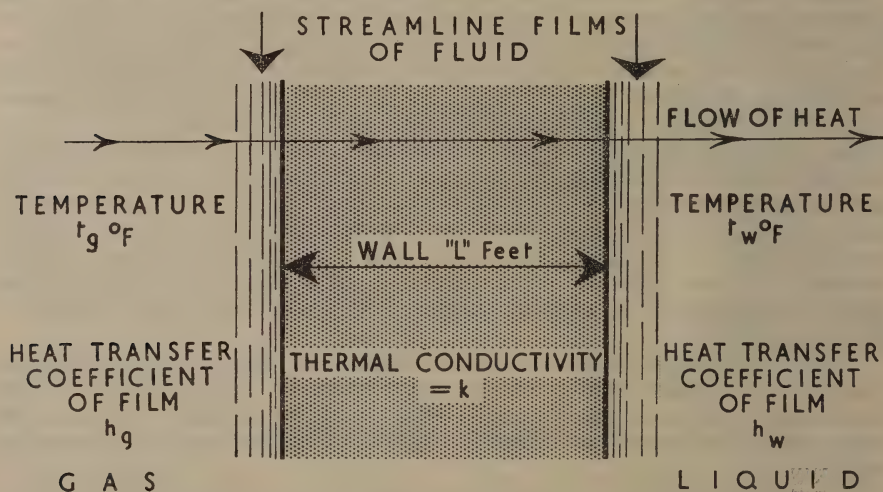


FIG. 7. Heat transmission through a plane wall separating two fluids.

Assuming an overall heat transfer coefficient, h , for the complete transfer of the heat from the hot gases through the boiler wall and into the water, the flow of heat, q , can be expressed as:

$$Ah (t_g - t_w) \text{ B.t.u. per hr.} \quad (26)$$

Substituting in Equation (25), we have

$$Ah (t_g - t_w) = \frac{A (t_g - t_w)}{\frac{1}{h_g} + \frac{L}{k} + \frac{1}{h_w}} \quad (27)$$

Dividing both sides by $A (t_g - t_w)$

$$h = \frac{1}{\frac{1}{h_g} + \frac{L}{k} + \frac{1}{h_w}} \text{ B.t.u./sq. ft. hr. deg. F.} \quad (28)$$

In Equation 28, h represents the *overall* heat transfer coefficient, incorporating the individual coefficients h_g , etc. It is common practice to represent this overall heat transfer coefficient by its own symbol, U . This avoids possible confusion with H , the symbol for *heat transfer rate*, and with h , for individual heat transfer coefficients.

Equation 25 could, therefore, be written in the form

$$q = UA (t_g - t_w) \quad (29)$$

Values of U for certain conditions are given in Table 5.

TABLE 5

<i>Conditions</i>	<i>Overall coefficient of heat transfer, B.t.u./sq. ft. hr. deg. F. (temp. diff.)</i>
Steam to water being heated	80-140
Hot water to water being heated	70
Steam to boiling water	140
Steam to thick fruit product	32
Cooling water by cold water and brine.. .. .	40-120
Hot oil to oil being heated	13-24
Hot oil to boiling water	30-40
Steam to water being heated in tubular heaters ..	100-160
Steam being condensed to water in tubular condenser jacket	140
Enamelled apparatus with low-pressure steam condensing outside with water boiling inside	up to 200
Do., but with hot oil as the heating medium	may fall to 10 or 20

THE RESISTANCE CONCEPT

The practical significance of Equation 25 is of supreme importance in heat transmission; it is analogous to that of the application of Ohm's Law in the transmission of electricity. The temperature potential, $t_g - t_w$, across the wall is comparable with electric potential—voltage—and the expression

$$\frac{1}{h_g} + \frac{L}{k} + \frac{1}{h_w}$$

is comparable with electrical resistance, the total resistance being the sum of the partial resistances. Continuing the simile, flow of heat is analogous to flow of electric current. Just as the reciprocal of the conductance in an electric wire measures the resistance of the wire to the passage of an electric current, so $\frac{1}{h}$, the reciprocal of the heat transfer coefficient (i.e. the reciprocal of the thermal conductance), measures the resistance to the flow of heat. It is an important fact that if the partial resistances differ greatly in magnitude only the largest resistance has a significant effect on heat transmission.

Example:

In a boiler tube the heat transfer coefficient on the water side, h_w , is of the order of 1,000 and the corresponding resistance, $\frac{1}{h_w} = 0.001$. The heat transfer coefficient on the flue side, h_g is only 6; the resistance, $\frac{1}{6}$, is thus 0.167.

Putting into Equation 28 the value 27.5 for the conductivity of mild steel and allowing for metal $\frac{3}{4}$ inch thick,

$$h = \frac{1}{0.167 + 0.0023 + 0.001} = 5.9,$$

a value virtually equal to the heat transfer coefficient on the flue side, which thus controls the heat transmission.

In a condenser, on the other hand, heat transfer coefficients on both sides of the heat-exchanging surface have high values; h_w on the water side may be approximately 1,000 and h_g on the steam side may be of the order of 2,000, both expressed as B.t.u./sq. ft. hr. deg. F.

The conductivity of the metal is in this case the governing factor. The maximum partial resistance is the controlling factor and should clearly, therefore, receive first consideration in any attempt to improve heat transmission.

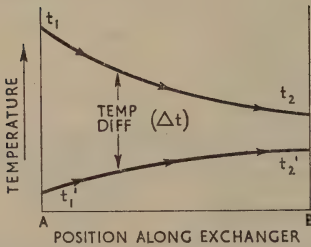
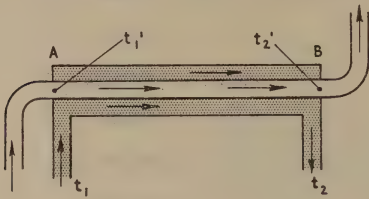


FIG. 8. Temperatures in a parallel-flow heat exchanger.

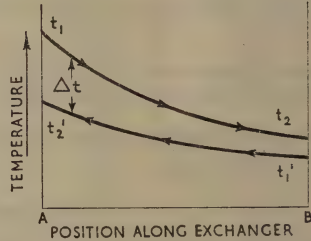
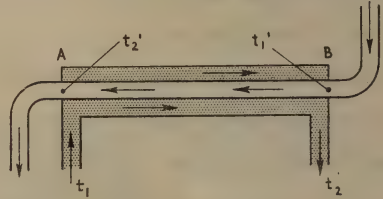


FIG. 9. Temperatures in a counter-flow heat exchanger.

HEAT EXCHANGE BETWEEN FLUIDS

This is effected in heat exchangers, to which further reference is made below. These may operate in *parallel*, or *counterflow*; typical temperature curves for these systems are shown in Figs. 8 and 9. Also, one material may flow at right angles to the second; the character of the flow is then referred to as *cross-flow*. Under conditions of constant heat transmission, i.e. with no marked fluctuations of temperature, a simple case to consider is that of two gases flowing through a heat exchanger, as in Fig. 8.

If q = heat transferred ; B.t.u./hr.

h (or U) = overall heat transfer coefficient ; B.t.u./sq. ft. hr. deg. F.

A = total heating surface ; sq. ft.

w = mass flow of the hotter gas ; lb./hr.

c = specific heat of the hotter gas ; B.t.u./lb. deg. F.

w' = mass flow of the colder gas ; lb./hr.

c' = specific heat of the colder gas ; B.t.u./lb. deg. F.

t_1 = inlet temperature of the initially hot gas ; ° F.

t_2 = outlet temperature of the hot gas ; ° F.

t_1' = inlet temperature of the initially cold gas ; ° F.

t_2' = outlet temperature of the cold gas ; ° F.

The amount of heat given up by the hotter gas is

$$q = wc (t_1 - t_2) \quad \dots \dots \dots (30)$$

and the heat received by the cooler gas,

$$q = w'c'(t_2' - t_1') \quad (31)$$

It will be seen, from Fig. 8, that the temperature difference between the hotter gas and the colder gas is not the same at all points of the exchanger. It is, therefore, convenient to assume a mean temperature difference Δt . This makes it possible to express the heat transfer as follows :

$$q = UA\Delta t \quad (32)$$

Where U is the overall heat transfer coefficient.

Since the heat given up must be equal to the heat absorbed, the right-hand sides of Equations 30, 31 and 32 must be equal to each other; thus

$$UA\Delta t = wc(t_1 - t_2) = w'c'(t_2' - t_1') \quad (33)$$

from which the heating surface, A , is given by either

$$A = \frac{wc(t_1 - t_2)}{U\Delta t} \quad \text{or} \quad \frac{w'c'(t_2' - t_1')}{U\Delta t} \quad (34)$$

It can be shown by integration that for parallel flow the mean temperature difference, Δt ,

$$= \left[(t_1 - t_1') - (t_2 - t_2') \right] \div 2.303 \log \frac{t_1 - t_1'}{t_2 - t_2'} \quad (35)$$

For counterflow,

$$\Delta t = \left[(t_1 - t_2') - (t_2 - t_1') \right] \div 2.303 \log \frac{t_1 - t_1'}{t_2 - t_2'} \quad (36)$$

Δt , as found from Equation 35 or Equation 36, is defined as the *log mean temperature difference*.

However, if the inlet and outlet temperatures of the fluids do not differ widely, the arithmetical mean, i.e., for parallel flow $[(t_1 - t_1') + (t_2 - t_2')] \div 2$, is sufficiently accurate.

Example:

In a counter-flow heat exchanger where hot combustion products are used to preheat air, the rates of flow of waste gases and air are, respectively, 35,000 and 32,000 cu. ft./hr. measured at 60° F. The waste gas enters the recuperator at 1,470° F. (800° C.) and air entering at 70° F. has to be pre-heated to 1,000° F. *What is the temperature of the waste gases at the exit from the appliance and what is the area of heating surface required?*

The problem involves a knowledge of the heat capacities of the gases and air in the ranges of temperature involved, and of the overall coefficient of heat transfer, U , which normally has to be calculated from (a) the heat transfer coefficients by convection and gas radiation on the waste gas side, (b) the conductance of the refractory tile, and (c) the heat transfer coefficient on the air side. These individual coefficients could be calculated using the formulae given earlier in this chapter but for the sake of simplicity the value of U is taken to be 1 and the respective specific heats (on a volume basis) 0.0215 and 0.0197 B.t.u./cu. ft. deg. F. for waste gas and air.

Accordingly, working in terms of volumes of gases instead of weights (which were used in Equations 32-34)

$$q = 0.0215 \times 35,000 (1,470 - t_2) = 0.0197 \times 32,000 (1,000 - 70) \\ = 586,270 \text{ B.t.u./hr.,}$$

from which $t_2 = 691^\circ \text{ F.}$

From the complete knowledge so far gained of the temperature conditions, Δt (Equation 36) is 539° F. and

$$A = \frac{q}{U\Delta t} = \frac{586,270}{1 \times 539} = 1,087 \text{ sq. ft.}$$

In certain types of heat exchangers the transfer of heat is intermittent. In such cases heat is stored within the structure (e.g. chequer brickwork).

The problem of calculating the heat exchange is beyond the scope of this book, since its solution involves a study of the fluctuating flow of heat. For more detailed treatment of the subject the reader is referred to the work of Heiligenstaedt⁶, Schack³ and Rummel⁷, and for applications to practice to that of Barnes and Sarjant⁸.

RADIATION

Conduction and convection represent transfer of energy from particle to particle by direct contact. Energy is transmitted from a hot body by radiation also and it can be transmitted by radiation to another body separated from it by a medium (e.g. air) transparent to the radiation. The emission of heat from the fire in a furnace when the fire box door is opened is a good example.

The radiations involved in the transfer of heat cover a 'spectrum' which is in effect an extension, beyond the red end, of the spectrum of visible light. Wave lengths, whether of visible light or invisible heat radiation, are measured in Ångstrom units (Å), the visible spectrum extending from the violet end (the wave length of violet light being about 4,000 Å) to the red portion of the visible spectrum in the region of 7,000 Å. The Ångstrom unit is 10^{-10} metres. Radiation of wave lengths longer than 7,500 Å. are those of the *infra-red* portion of the spectrum, invisible to the human eye but able to affect photographic plates. Thermal radiation occurs within the range 7,500–53,000 Å., a matter of considerable practical importance in industrial heating.

It is important to realise that all matter—solids, liquids and gases—can radiate heat; invisible hot furnace gases, for example, radiate heat to their surroundings.

In the transfer of heat between a hot body and a cold body conduction, convection and radiation are all affected by the difference between the temperatures of the bodies. The temperature level—i.e. whether high temperature or low temperature—also influences the rate of heat transfer by all three processes but it is particularly significant in the case of radiation. As will be seen below, conduction and convection make the major contribution to total heat transfer at lower temperatures; at very high temperatures radiation plays the predominating part.

Although radiation is more striking within high temperature ranges, it is actually a factor in heat transfer even at relatively low temperatures, e.g. from the relatively cool surface of a lagged steam pipe. The radiating surface need not be visibly red-hot or even hot in the infra-red zone, in order to radiate heat.

The capacity of a body to emit (radiate) or absorb heat energy is of particular significance. If a body absorbs all the radiant energy impinging on its surface it is termed a *black body*. The *absorptivity* (α) of a black body is allocated the maximum possible value, unity. Conversely, such a body is also a perfect radiator, an emitter of radiant energy, and it is stated to have an *emissivity* (ϵ) of unity. A good absorbing surface is a good radiating surface.

The use of the word 'black' can be misleading; it does not refer to the colour, or absence of colour, of the body.

Black body conditions are approached in a closed furnace chamber, where any radiation not at first absorbed is repeatedly reflected and partly absorbed, until it is finally all absorbed. Even so good an absorber as lamp black is not a perfect black body; nevertheless it absorbs 0.97 of black body absorption and can also radiate that proportion, i.e. its emissivity is also 0.97.

Many bodies, such as polished metals are poor absorbers and, accordingly, poor radiators, their emissivity being less than 0.1 of that of a black body.

Stefan found experimentally that the total radiant energy emitted by a hot body varied as the fourth power of the Absolute temperature of the body. Boltzmann developed the theoretical basis, the result being the *Stefan-Boltzmann law*.

Applying the law to a black body at temperature T_1° Abs., within black body surroundings at T_2° Abs., the heat transfer is given by the equation—

$$q = 17.13 \times 10^{-10} \times A (T_1^4 - T_2^4) \quad \text{. (37)}$$

where q = heat transfer; B.t.u./hr.,

$$T_1 = t_1^\circ \text{ F.} + 460,$$

$$T_2 = t_2^\circ \text{ F.} + 460,$$

A = area of the body; sq. ft.,

Using c.g.s. units, the equation is

$$q = 13.6 \times 10^{-11} \times A (T_1^4 - T_2^4) \text{ cal./sec.} \quad \text{. . . . (38)}$$

where A = sq. cm.

$$T_1 = t_1^\circ \text{ C.} + 273$$

$$T_2 = t_2^\circ \text{ C.} + 273.$$

A more convenient form of Equation 37 is

$$q = 0.1713 A \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] \text{ B.t.u./hr.} \quad \text{. . . (39)}$$

When the radiating and absorbing surfaces are not 'black' or when one of the bodies is not completely surrounded by the other radiating or absorbing surface, it is necessary to take into consideration the relative sizes, shapes and dispositions of the surfaces, as well as their emissive properties.

For example, the expression *rate of heat transfer per unit area* invariably applies to the area of the enclosed (i.e. the smaller) surface.

The heat transfer per unit area of the larger surface may be found by calculating the total heat exchange from the area of the smaller surface and dividing this by the area of the larger surface.

For a surface having no re-entrant angles, the total area, whether plane or curved, is the effective radiating surface.

For a surface having re-entrant angles, such as irregular-shaped stock in an annealing furnace, or many furnace structures, the larger area due to the concavity must not be included in the total area; the area that must be taken is defined as the least surface that could be built across the concave portion.

The net radiation between two surfaces is dependent not only upon the emissivity of the radiating surface, but also upon that of the surface receiving the radiation. For two parallel mutually radiating surfaces, having emissivities ϵ_1 (for the hotter) and ϵ_2 (for the cooler), the net emissivity, ϵ ,

$$= \frac{\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2 - \epsilon_1 \epsilon_2} \quad \text{. (40)}$$

The problem may also be tackled by applying the geometric factors which are used in equations of the same form as Equations 37–39. For a full account of their derivation and application, the reader is referred to the chapter on Radiant Heat Transmission by H. C. Hottel, in McAdam's "Heat Transmission".

In addition, the relative sizes of the surfaces influence the extent of radiation. Equation 40 gives the minimum value for the emissivity; the maximum value is ϵ_1 . The maximum value represents the heat loss from a hot surface very small compared with its surroundings, under which condition the emissivity of the (cooler) surroundings ϵ_2 has practically no effect on the heat loss. The minimum value represents the heat loss from a substance nearly as big as its surroundings. The problem also becomes more complicated in practice because of the three following laws.

KIRCHOFF'S RADIATION LAW

Kirchoff's law states that the radiating capacity of a given body, represented by the emissivity ϵ , is for a given temperature and a given wave length proportional to the absorbing capacity of the body. In other words a body at a certain temperature will radiate in proportion to its ability to absorb. Thus polished metals absorb only a small percentage of the radiation falling upon them and have a small relative blackness, whereas lamp black being nearly a perfect radiator approaches being a perfect absorber.

LAMBERT'S RADIATION LAW

Lambert's law states that the radiation from a surface in a direction at an

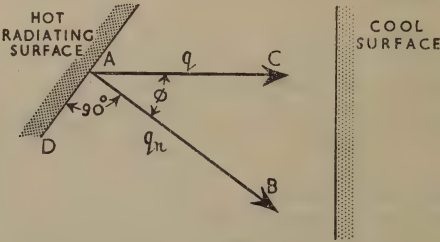


FIG. 10. Lambert's law of radiation.

angle with the surface varies as the cosine of the angle, ϕ , between the direction of radiation and the normal to the surface (Fig. 10). The radiation in the given direction is

$$q_n \cos \phi \dots \dots \dots (41)$$

where q_n is the radiation normal to the surface.

INVERSE SQUARE LAW

The intensity of radiation from a point source of radiant energy decreases with the square of the distance from the point source.

Another difficulty in the computation of radiation is that some bodies exhibit different absorptivities for different wave lengths.

For the full treatment of this subject reference should be made to standard works on heat transmission. In practice, calculations on the basis of Equation 37, using the emissivity constants given in Table 6, serve a useful purpose in many problems without recourse to the more exact treatment referred to above.

The lower the value of the emissivity ϵ , the less is the heat lost from a hot body or the heat gained by a cool body. If under black body conditions the temperatures are such that the heat transfer rate, H , =100 B.t.u. per square foot per hour, the heat lost from a steel sheet surface under the same conditions would be 82 B.t.u. per square foot per hour, and that lost from a surface of polished copper would be no more than 5.2 B.t.u. per square foot per hour.

TABLE 6. NORMAL TOTAL EMISSIVITY OF SOLID SURFACES¹.

Surface	Temperature deg. F.	Emissivity (black body=1)
Aluminium:		
Commercial sheet	212	0.09
Oxidized at 1,110°F.	390-1,110	0.11-0.19
Brass:		
Polished	212	0.06
Dull plate	120-660	0.22
Copper:		
Polished	212	0.052
Plate heated at 1,110° F.	390-1,110	0.57
Iron:		
Polished	800-1,880	0.14-0.38
Oxidized at 1,110°F.	390-1,110	0.64-0.78
Rough ingot	1,700-2,040	0.87-0.95
Steel:		
Sheet	75	0.82
Shiny oxide layer calorized at 1,110° F.	390-1,110	0.52-0.57
Plate, rough	100-700	0.94-0.97
Molten slightly oxidized surface	2,840-3,110	0.27-0.39
Nickel:		
Electroplated		
Polished	74	0.045
Not polished	68	0.11
Plate oxidized at 1,110° F.	290-1,110	0.37-0.48
Stainless steel:		
Polished	212	0.074
'18-8' after 42 hr. at 980° F.	420-980	0.62-0.73
Alumina-silica brick:		
80-58 Al ₂ O ₃ , 16-38 SiO ₂ , 0.4 Fe ₂ O ₃	1,850-2,850	0.61-0.43
36-26 Al ₂ O ₃ , 50-SiO ₂ , 1.7 Fe ₂ O ₃	—	0.73-0.62
61 Al ₂ O ₃ , 35 SiO ₂ , 2.9 Fe ₂ O ₃	—	0.78-0.68
Brick:		
Building	1832	0.45
Fireclay	1832	0.75
Carborundum:		
(87% SiC, density 2.3)	1,850-2,550	0.192-0.82
Magnesite refractory brick	1832	0.38
Paints:		
Black or white lacquer	100-200	0.80-0.95
Oil paints, all colours	212	0.92-0.96
Plaster:		
Rough lime	50-190	0.91
Porcelain—glazed	72	0.92

EFFECT OF TEMPERATURE ON RADIATION

The practical effect of the Stefan-Boltzmann law is that the rate of heat transmission by radiation varies as the difference between the fourth powers of the absolute temperatures of the hot and cold bodies. Conduction, on the other hand, varies as the first power of the temperature difference, and natural convection with the 1.25th power. It is thus evident that the higher the temperature difference between the hotter and cooler surfaces, the more important relatively is the transfer of heat by radiation.

It is thus an established principle that for rapid transfer of heat by radiation, the temperature of the radiating surface should be as high as possible. An application of this principle is the use of pre-heated air to raise flame temperatures (cf. Fig. 4, Chapter 7).

To make this clear by a numerical example, suppose that heat is to be transferred by radiation from a surface at high temperature to a surface at

350° F., the value of ϵ being 0.56. The calculated heat transfer is as follows:

Temperature of hot surface ° C.	800	1,000	1,200	1,500
.. .. . ° F.	1,470	1,830	2,190	2,735
Heat transferred, H—B.t.u./sq. ft. hr.	13,000	24,400	48,100	101,000
Relative value of H	1	1.88	3.7	7.8
Relative value of hot surface absolute temperature, T_1	1	1.19	1.37	1.65

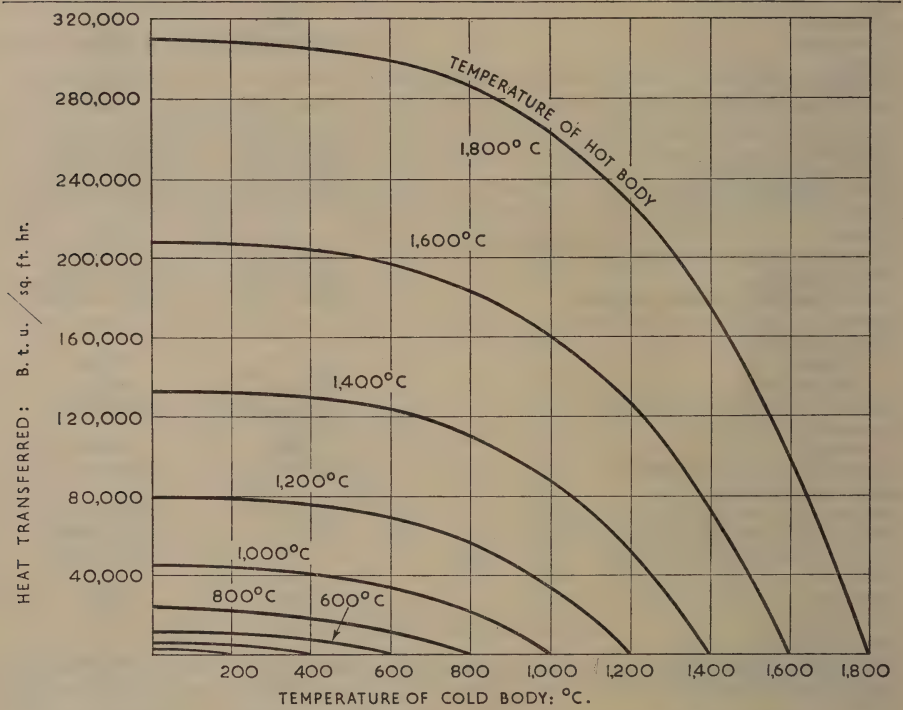


FIG. 11. Heat transfer by radiation from hot surfaces. ($\epsilon = 0.92$)

These points are illustrated in Fig. 11, which, it should be noted, gives the heat transfer, by radiation, for a body of emissivity 0.92, i.e. higher than the value 0.56 taken for the above example.

The high rate of radiation from luminous flames is due to the radiating surface of the carbon in these flames, and clearly the higher the temperature to which the carbon is heated, the greater will be the radiating effect.

RADIATION FROM A COKE FIRE

An example of the heat transfer from the surface of an incandescent fuel bed of coke, which is frequently used for heating vessels such as evaporating pans, is given in Table 7. From practical observations it has been established that temperatures of the surface of the fuel bed corresponding to rates of combustion of coke of 20 up to 106 lb. per square foot per hour are those given in the second line of the table, namely temperatures ranging from 1,232° to 1,509° C. The temperatures of the heat-absorbing surfaces range between 200° and 400° C. in such practice. The heat emission, according to the fourth power law, has been calculated for the two temperatures concerned by the use of Equation 37 and an emissivity coefficient of 0.9. The total potential heat in the coke corresponding to the rates of combustion applying are also shown,

together with the radiant heat emitted reckoned as a percentage of this total value. The calorific value of the coke has been taken as 12,500 B.t.u. per lb. It is to be noted that at the lower rates of combustion the direct radiant heat is approximately 33 per cent. of the total available heat, but that at the higher rates of combustion the proportion of radiant heat approaches a much lower value, e.g. 12 per cent. This is due to the fact that at the higher rates of combustion the mass of the gas emerging from the fuel bed is increased, and carries with it a higher proportion of the total available heat as either potential or sensible heat in the hot gases.

TABLE 7. RADIATION FROM A COKE FIRE

Rate of combustion—lb./sq. ft. hr.	20	51	71	106
Temperature of coke bed—° C.	1,232	1,383	1,442	1,509
Heat transmission to surface (thousand B.t.u./sq. ft. hr.) by radiation				
at 200° C.	83.3	122.3	140.9	164.3
at 400° C.	80.5	119.5	138.2	161.5
Rate of total heat release from coke (thousand B.t.u./sq. ft. hr.)	250	637.5	887.5	1,325
Per cent. of heat radiated to total heat developed				
Cold surface at 200° C.	33.3	19.2	15.9	12.4
at 400° C.	32.2	18.8	15.6	12.2

FROM RADIATION OF CARBON DIOXIDE AND WATER VAPOUR IN FURNACE GASES

Hot gases radiate heat even when no combustion is taking place. Good radiating gases include carbon dioxide, water vapour and hydrocarbons; carbon monoxide is a relatively poor radiator of heat. For most practical purposes, hydrogen, oxygen and nitrogen are non-radiators. The radiation effect of a non-luminous flame is accordingly governed mainly by its carbon dioxide and water vapour contents.

The transfer of heat from the gas to the wall is an exchange process, since heat is also returned from the wall to the gas. Because of the thickness of the layer of gas, some of the heat radiated by the molecules of CO_2 and water vapour are absorbed by other of the molecules before it can reach the wall. Heat exchange in a combustion chamber containing the non-luminous products of combustion proceeds as follows :

(i) The gas radiation to the walls of the chamber depends upon the amount of radiating gas between the walls, that is to say, on the concentrations of the CO_2 and water vapour present, on the thickness of the gas layer and on the pressure and temperature of the gas.

(ii) Of the heat radiated by the gases, only a fraction is retained by the wall, the remainder being reflected back.

(iii) At the same time, there is heat exchange between the hot walls, radiating according to the Stefan-Boltzmann Law, if temperature differences exist. Only a relatively small proportion of this heat is absorbed by the gases. If the wall is hotter than the gas, the latter becomes heated; if the wall is cooler, the wall becomes heated by gas radiation.

A convenient method of evaluating gas radiation—due to Hottel⁹—involves the evaluation of the gas emissivity coefficients and applying them to a modified fourth-power law correcting for the influence of the gas composition in respect of CO_2 and water vapour content, and for the thickness of the gas layer.

The symbols used in applying this method are as follows :

- q = rate of heat transfer due to gas radiation ; B.t.u./hr.
 A = area of surface exchanging radiation with the gas ; sq. ft.
 T_g = Absolute temperature of the gas ; $t_g^\circ \text{F.} + 460$.
 T_s = Absolute temperature of the surface ; $t_s^\circ \text{F.} + 460$
 ϵ_g = emissivity of the gas (dimensionless).
 α_g = absorptivity of the gas (dimensionless).
 P_c = partial pressure of carbon dioxide ; atmospheres.
 P_w = partial pressure of water vapour ; atmospheres.
 L = beam length of gas radiation ; feet.
 ϵ_s = emissivity of heat exchanging surface.
 ϵ'_s = effective emissivity = $\frac{\epsilon_s + 1}{2}$
 ϵ_c = emissivity of CO_2 content of the flue gases.
 ϵ_w = emissivity of H_2O vapour of the flue gases.

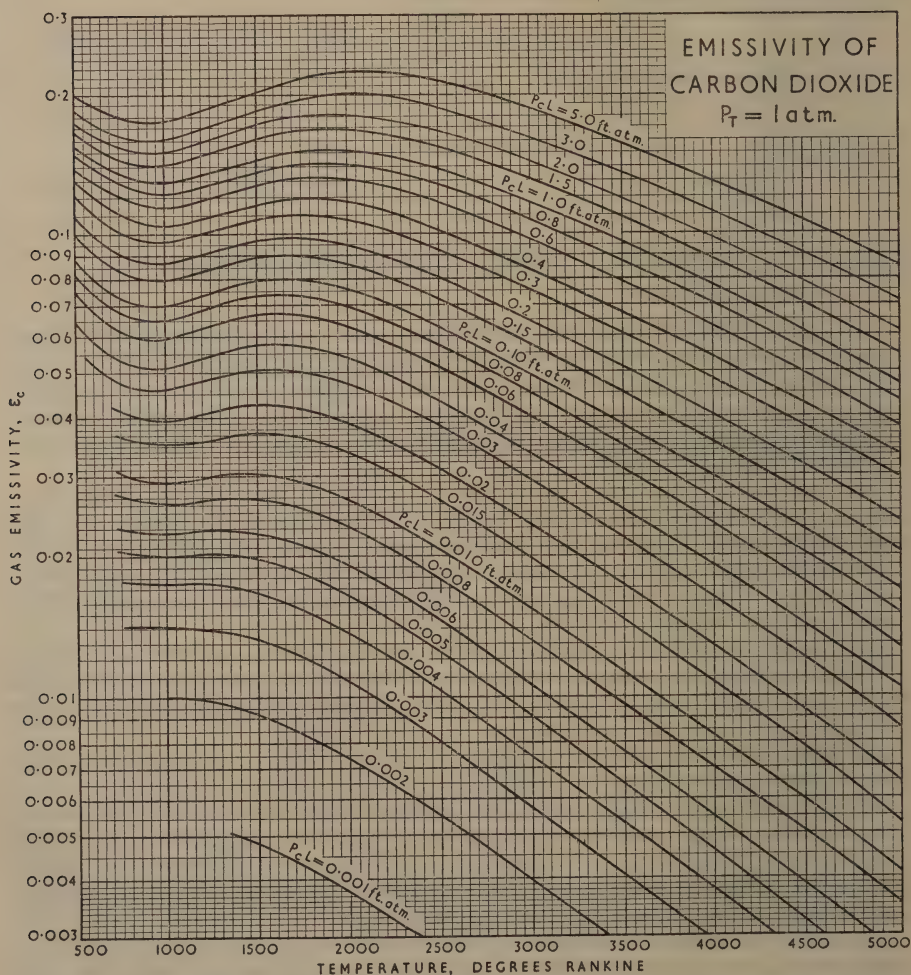


FIG. 12. Emissivity of CO_2 for various values of $P_c L$.

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The complete calculation is complicated, but although it can be shortened in certain circumstances it will be given in full here step by step.

A relation, originally developed by Schack and amended by Hottel, exists between gas emissivity, temperature, and the product of the partial pressure of the gas and the thickness of the gas layer that is emitting the radiation. This relationship is the basis of Figs. 12 and 13.

From these figures, subject to certain corrections for which Figs. 14 and 15 are used, it is possible to compute the coefficient of emissivity of the gas ϵ_g .

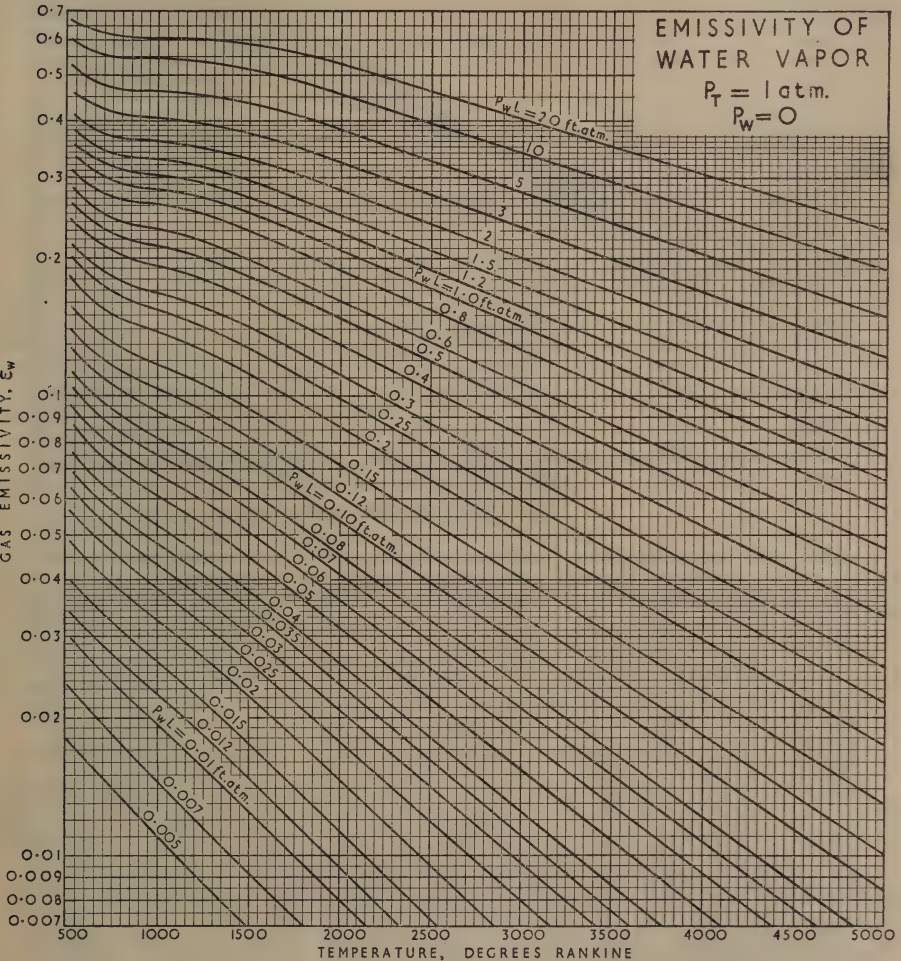


FIG. 13. Emissivity of water vapour for various values of $P_w L$.

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The effective emissivity of the surfaces (ϵ'_s) must also be taken into account.

The gases absorb radiation emitted from the walls, and the value of the coefficient of absorption of the gas for this radiation, α_g , must also be determined.

These coefficients are then used in Equation 39 as follows:

$$q/A = H = 0.1713 \epsilon'_s \left[\epsilon_g \left(\frac{T_g}{100} \right)^4 - \alpha_g \left(\frac{T_s}{100} \right)^4 \right] \text{B.t.u./sq. ft. hr.} \quad (41)$$

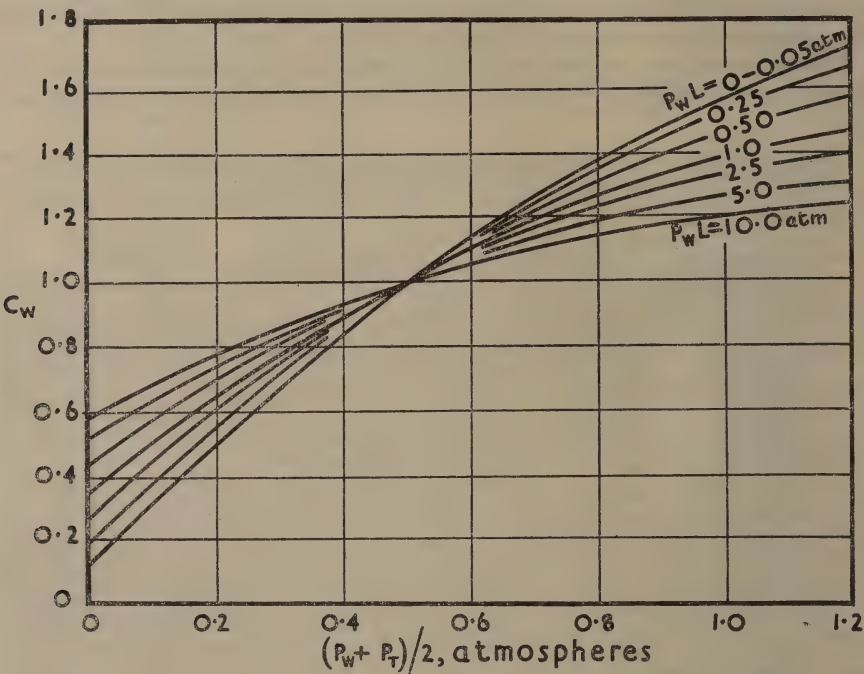


FIG. 14. Correction factor, C_w , for converting emissivity of water vapour to values of P_w and P_t other than 0 and 1 atm. respectively
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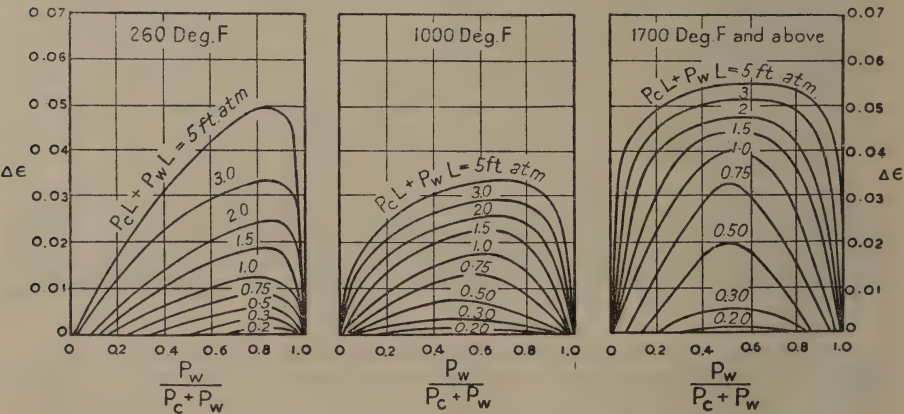


FIG. 15. Chart for evaluating the absorption of gas radiation by the gas itself.
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The steps by which this calculation is made are now given.

- (1) The partial pressures P_o and P_w (in atmospheres) of the radiating gases CO_2 and H_2O are derived from the percentage composition by volume.

(2) The effective thickness of the gaseous layer is calculated. In Figs. 12 and 13 the same thickness of gas in all directions is assumed. This is not generally the case and the effective thickness, L , is found from the empirical expression.

$$L = \frac{4 \times \text{vol. of gas space}}{\text{area of bounding walls}} \times 0.85$$

Table 8 enables this value to be calculated for several industrially important shapes.

TABLE 8. EQUIVALENT THICKNESS L FOR NON-LUMINOUS GAS RADIATION FROM LAYERS OF DIFFERENT SHAPES

1	2	3	
Shape	Characteristic dimension, X	Factor by which X in column 2 is to be multiplied to give equivalent L for hemispherical radiation	
		Calculated by various workers	Calculated from $4 \times 0.85 \times \text{volume} \div \text{area}$
Sphere	Diameter	0.60	0.57
Cube	Side	0.60	0.57
Infinite cylinder, radiating to walls	Diameter	0.90	0.85
Ditto, radiating to centre of base ..	Diameter	0.90	0.85
Cylinder, height=diameter, radiating to whole surface	Diameter	0.60	0.57
Ditto, radiating to centre of base ..	Diameter	0.77	0.57
Space between infinite parallel planes..	{ Distance apart }	1.80	1.70
Space outside infinite bank of tubes with centres on equilateral triangles, tube diameter=clearance	Clearance	2.80	2.89
Ditto, but tube diameter = one-half clearance	Clearance	3.80	3.78
Ditto, with tube centres on squares, and tube diameter=clearance	Clearance	3.50	3.49
Rectangular parallelepiped, $1 \times 2 \times 6$, radiating to:	} Shortest edge	{	
2 \times 6 face			1.06
1 \times 6 face			1.06
1 \times 2 face			1.06
All faces			1.02
Infinite cylinder of semicircular cross-section, radiating to centre of flat side	Diameter	0.63	0.52

- (3) The values of P_oL and P_wL are then calculated.
- (4) The coefficient of emissivity due to CO_2 , i.e. ϵ_c , is then read off from Fig. 12 for the ascertained value of P_oL at the required gas temperature.
- (5) In the same way the value of ϵ_w is read off from Fig. 13. This value, however, is subject to a correction because the emissivity of water vapour ϵ_w , depends not only on the temperature and on P_wL , but also on the concentration of water vapour in the gases. Fig. 13 is drawn for the ideal condition of $P_w=0$, and allowance for the real value of P_w must be made by multiplying the value of ϵ_w read from Fig. 13 by a factor C_w read from Fig. 14.
- (6) The combined values of ϵ_c and ϵ_w represent the radiating power of the gas, but since substances that radiate also absorb radiation, a further correction must be made for the radiation absorbed by the gas. This

correction, $\Delta\epsilon$ is read from Fig. 15.

Then,
$$\epsilon_G = \epsilon_c + \epsilon_w - \Delta\epsilon.$$

- (7) By similar calculations, the value of the absorptivity coefficient,

$$\alpha_G = \alpha_c + \alpha_w - \Delta\alpha,$$

is determined, using the temperature of the surface, not that of the gas, when reading the coefficients from Figs. 12 and 13.

This method of determining α_G is correct if the gas is appreciably hotter than the surface, and it applies to most furnace conditions. If a more accurate method is needed, the values used for reading from Figs 12 and 13 are not $P_c L$ and $P_w L$, but these values multiplied by the ratio (Absolute temperature of surface) : (Absolute temperature of gas),

$$\text{i.e. } P_c L \times (T_s/T_G) \text{ and } P_w L \times (T_s/T_G)$$

The values thus obtained are then multiplied by $(T_G/T_s)^{0.65}$, an empirical correction factor derived by Hottel.

- (8) If the bounding surfaces differ substantially from black body conditions, the factor ϵ'_s , the emissivity of the surface must also be introduced as in Equation 41. Since some of the gas radiation initially reflected from the surface would have further opportunity for absorption at a bounding surface, because much of the reflected radiation passes unabsorbed through the gas, the effective value of ϵ'_s lies between the value for the emissivity of the surface and that of a black body. For most industrial applications,

$$\epsilon'_s = \frac{\epsilon_s + 1}{2}$$

- (9) Equation 41 is then applied.

Table 8 is taken from the paper on heat transmission by Lander⁴ (*loc. cit.*).

Example: It is required to ascertain the gas radiation to the crown of a furnace chamber under the following conditions :

Dimensions of furnace: 12 feet long \times 4 feet wide \times 2 feet mean height.

Composition of gas: CO_2 13.2 per cent.

H_2O 12.1 " "

$\text{O}_2 + \text{N}_2$ 74.7 " "

Mean temperature of gases: 2,000° F. (1,090° C.)

Mean temperature of furnace crown : 1,500° F. (815° C.)

- (1) Partial pressures: CO_2 0.132 atmos. (P_c)

H_2O 0.121 " (P_w)

- (2) The shortest edge is 2 feet, and from Table 8 the factor by which it must be multiplied is 1.06, thus $L=2.12$.

- (3)
$$P_c L = 0.132 \times 2.12 = 0.28$$
$$P_w L = 0.121 \times 2.12 = 0.256$$

- (4) ϵ_c (from Fig. 12) = 0.091.

- (5) ϵ_w (from Fig. 13) = 0.084.

The factor, C_w , (from Fig. 14) is 1.08.

$$\epsilon_w = 0.084 \times 1.08 = 0.091.$$

- (6) Correction for gaseous absorption (Fig. 15).

$\Delta\alpha$ may be taken as equal to $\Delta\epsilon$, i.e. 0.022. Then,

$$\epsilon_G = 0.091 + 0.091 - 0.022 = 0.160.$$

- (7) Determination of α_G

$$P_c L \times (T_s/T_G) = 0.28 \times 1,960/2,460 = 0.23.$$

Emissivity at 1,500° F. read from Fig. 12 = 0.10

$$\text{Hence } \alpha_c = 0.10 \left(\frac{2,460}{1,960} \right)^{0.65} = 0.116$$

$$P_w L \times (T_s/T_g) = \frac{0.256 \times 1,960}{2,460} = 0.204$$

Emissivity at 1,500° F. read from Fig. 13 = 0.090

$$\text{Hence } \alpha_w = 0.09 C_w \left(\frac{2,460}{1,960} \right)^{0.65} = 0.104 \times 1.08 \text{ (from 5)} \\ = 0.112$$

From Fig. 15 $\Delta\alpha = \Delta\epsilon$ at 1,500° F. = 0.02

Whence,

$$\alpha_g = 0.116 + 0.112 - 0.020 = 0.208$$

(8) For a furnace interior ϵ'_s may be taken as 0.9.

$$H = 0.1713 \times 0.9 [0.160 (2,460/100)^4 - 0.208 (1,960/100)^4] \\ = 4,300 \text{ B.t.u./sq. ft. hr.}$$

Hence for these conditions, the coefficient of gas radiation is 4,300/500 = 8.6 B.t.u./sq.ft.hr.deg.F., exclusive of the effect of radiation transmitted to the roof by refractory surfaces.

RADIATION FROM LUMINOUS FLAMES

Luminous flames are produced by restricting the air supply so that the hydrocarbons present in the gas are cracked in the absence of sufficient oxygen for combustion, to produce solid particles of carbon; the mechanism of the reaction is not yet completely understood. The combustion of a luminous flame is more protracted than that of a similar non-luminous flame; as a result a longer flame is produced from a similar flux of combustible matter. The small particles of carbon absorb heat from the surrounding atmosphere of hot gas and radiate energy to the enclosing surface.

With luminous flames it is more difficult to relate any quantitative analyses of the heat emission to the effect produced in the furnace. A study of the subject by application of the fourth power radiation law to the incandescent particles of carbon in flames produced by pulverized coal has shown that inflation of the coal particles during combustion, producing *cenospheres* eight times as large as the parent particles, has a favourable influence on flame radiation.

Similar results have been found in the combustion of natural gas, and in the measurement of the emissivity of the flame produced in an oil-fired open-hearth furnace. The International Flame Radiation Committee in an experimental programme designed to investigate luminous flames has shown that though the production of luminosity in flames from liquid fuels depends on the carbon : hydrogen ratio of the fuel it is more affected by the mode of air and fuel mixing. Thus the air : fuel ratio, the momentum of the fuel, air and atomizing agent play an important part in determining the flame emissivity. It is not yet possible, by methods other than empirical, to calculate the radiation from the luminous flame in as simple a manner as for that from non-luminous flames.

When coke oven gas is enriched, e.g. with tar or pitch creosote, high emissivities—of the order of 0.9—are obtained. This has immediate application in the firing of open-hearth furnaces.

Schack described an instance of a rolling mill furnace, heated by coke oven gas. When the flame was rendered luminous its temperature fell by 180 deg. F. but, owing to its better radiating properties, the surface temperature of the

furnace crown rose by 145 deg. F. In such a furnace the heat transfer to the relatively cold walls is high at first, and the temperature of the waste gas is low. Soon, however, the temperature of the indirect heating surface rises, and the heat transferred to these surfaces decreases as a result of the smaller difference between the temperatures of the combustion gases and the surfaces; the temperature of the waste gas then correspondingly rises. The distribution of the heat transferred in furnaces operating at re-heating temperatures (1,150–1,300° C.) has been estimated by Schack to be as follows:

	<i>Percentage of total heat transfer</i>			
Direct gas radiation	54
Furnace wall and crown radiation	34
Convection	12
				<u>100</u>

Heat transfer by convection has only a subordinate influence in such furnaces.

PRACTICAL ASPECTS OF HEAT TRANSMISSION

HEAT EXCHANGERS

In all practical problems of heat transfer heat must be transferred from a hot substance (e.g. a fluid) to a cooler substance. This is effected in heat exchangers, of which there is a very large range of types.

Heat exchangers are usually classified into two groups;

- (a) those in which heat is transferred from one fluid to another continuously;
- and (b) those in which hot fluids impart most of their heat to a suitable heat-storing solid—generally refractory brick—from which it is subsequently abstracted by interrupting the flow of the incoming hot fluid and substituting the cooler fluid that has to be heated.

To the first class belong recuperators, condensers, air heaters, and economisers; to the second class belong regenerators, usually applied to the pre-heating of gas and air in high temperature melting furnaces and in blast furnace stoves.

Recuperators

Continuous heat transfer between fluids can be carried out in recuperators. These may be of metal or refractory construction, dependent on the temperature of operation. There are no reversals required, but the maximum temperature for which this type of heat recovery appliance can be used is lower than that for a regenerator.

Regenerators.

A regenerator usually consists of a mass of chequer brickwork constructed in a separate chamber through which the waste gases from the furnace descend to heat the chequers. They then pass to a reversing valve on their way to the chimney. In reheating and melting furnace practice and in certain types of kiln a regenerative system is applied to furnaces having two sets of ports, one at each end of the furnace chamber, through which the direction of the gases is periodically reversed.

When only air is pre-heated there are two regenerator chambers, one taking up the waste heat from the hot gases, and the other pre-heating the air for combustion. Each regenerator thus has a heating cycle on waste gas and a cooling cycle on air. A blast furnace stove operates on the same principle except that gas is burnt in a combustion chamber built into the stove to provide the heat storage in the chequer brickwork during the heating cycle,

the combustible gas being shut off during the cooling cycle when the air for the blast is being pre-heated.

Fig. 16 depicts a regenerative system applied to an open-hearth steel furnace, or a glass furnace in which both air and gas are pre-heated. With the valves set as shown, air and gas flow up the left-hand regenerator where they are pre-heated by the hot chequer bricks to perhaps 900°–1,000° C. Each issues

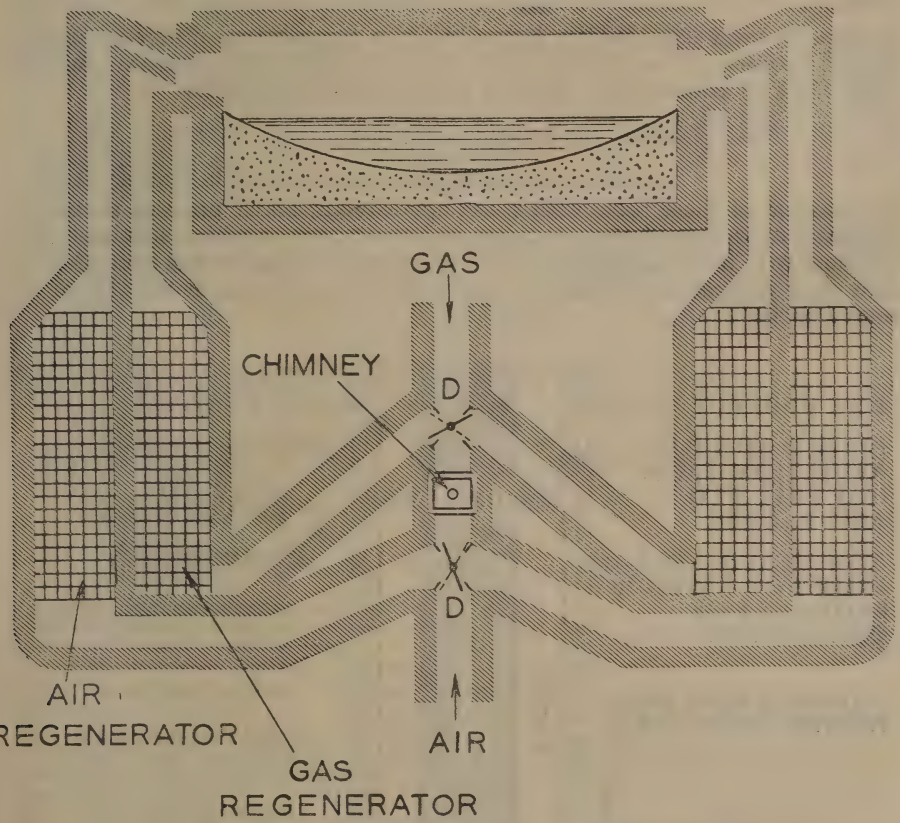


FIG. 16. Diagrammatic illustration of a regenerative furnace.

through its appropriate ports and combustion takes place in the furnace. The products of combustion pass down through the right-hand regenerators, giving up their heat to the chequers, and then flow to the chimney. After a suitable period, the valves are changed to the dotted positions, when the flow of the gas and air is reversed. The cold gases now pass through the hot right-hand regenerators and the hot products of combustion leave the system through the cooled left-hand regenerators.

HEAT TRANSMISSION IN BOILERS

Evaporation in a boiler is sometimes referred to in terms of the equivalent energy produced in the form of steam. A boiler rating may, for example, be expressed in square feet of heating surface per boiler horse-power. For a heating surface of 10 sq. ft., this is equivalent to a rate of heat transmission of

$$\frac{34.5 \times 970.3}{10} \text{ i.e. } 3,350 \text{ B.t.u./sq. ft. hr.}$$

the evaporation of 34.5 pounds of water per hour "from and at 212° F." representing one boiler horse-power, and 970.3 being the latent heat of steam at 212° F. If the thermal conductivity of iron is 408 B.t.u./sq. ft. hr. deg. F./in. at a temperature of 400° F. and the boiler plate is $\frac{1}{16}$ inch thick, the temperature difference across the plate is only

$$\frac{3,350 \times 1/16}{408} \text{ i.e. } 0.82 \text{ deg. F.}$$

In experimental trials with a Heine boiler, a temperature difference of 41.5 deg. F. between the two surfaces of a tube $\frac{1}{8}$ inch thick was observed. Accordingly the heat transmission through the tube must have been

$$\frac{408 \times 41.5}{1/8} \text{ i.e. } 135,450 \text{ B.t.u./sq. ft. hr.}$$

= 140 lb. of steam "from and at 212° F." per sq. ft. hr.

Comparison of these rates with those operative in boiler practice shows the potential capacities of clean surfaces and the extent to which soot and scale interfere with heat transmission. The above rate of transfer was equivalent to that from a furnace at 2,640° F. and with a temperature of 800° F. on the sooted surface.

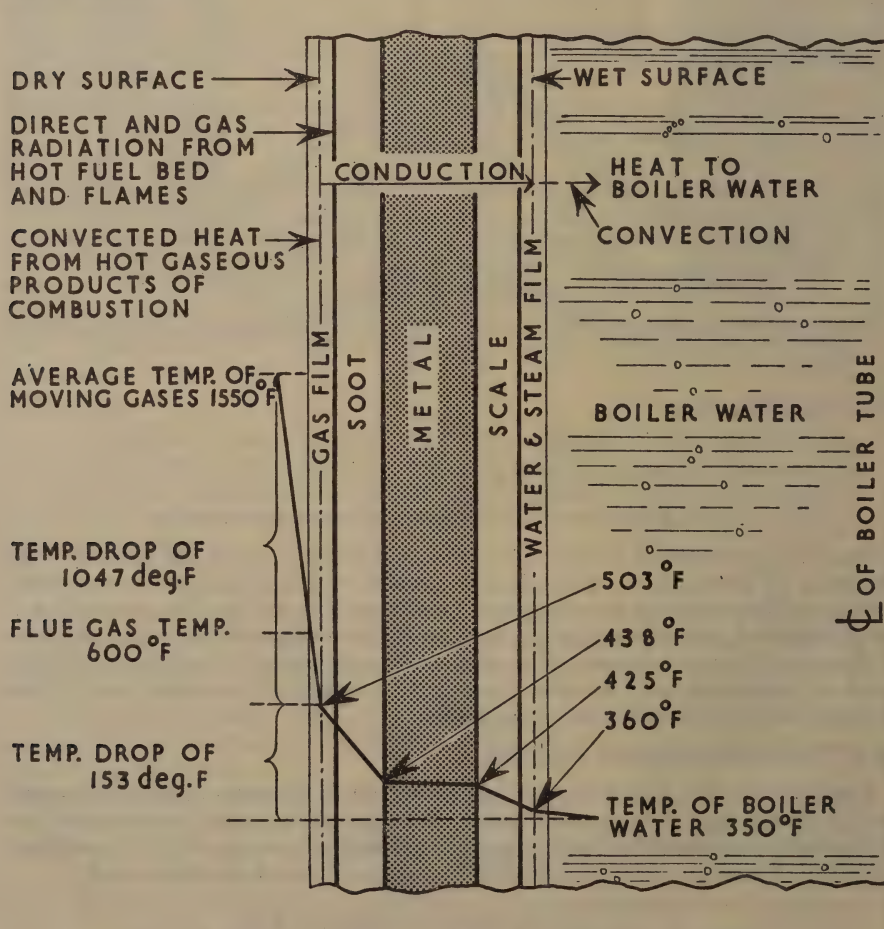


FIG. 17. Heat transmission from hot flue gases to boiler water

The data given in Fig. 17 give a picture of the temperature conditions in a boiler tube when the initial temperature of the gases is 2,500° F. and the boiler is working at 10 times a normal rate. From this diagram it will be seen that the process of getting the heat by radiation and convection through to the dry surface of the boiler tube is slow compared with that on the wet side. The course of the temperature conditions through the gas passages of a boiler is shown in Fig. 18 based on experimental observations on water-tube boilers. Heat is transmitted from the hot fuel bed and the adjoining refractory surfaces to boiler heating surfaces by direct radiation, from the products of combustion by gas radiation, and by convection. The heat transfer coefficient by convection rises from 1 to 12 B.t.u./sq. ft. hr. deg. F. as the rate of the flow of the gases increases. Because of this fact, waste heat boilers fitted with fire-tubes are usually equipped with high-power exhaust fans to give the high velocities needed for efficient heat transfer by convection.

A good example of the use of heat transfer by radiation is in the furnace of the locomotive boiler. The hot surface is the fuel bed, and the cold surface comprises the surface of the tube sheet, the crown sheet, the front sheet, and the plates on both sides of the fuel bed. Raising the furnace temperature from 2,000° F. to 3,000° F. will nearly quadruple the amount of heat imparted by

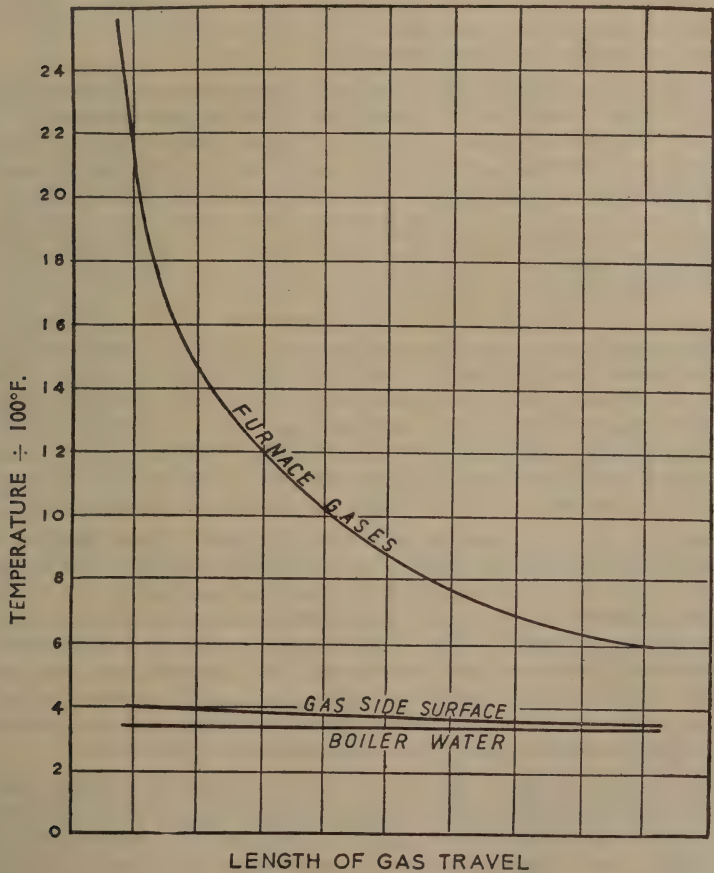


FIG. 18. Temperature drop through the gas passages of a water-tube boiler.

radiation. A drop of temperature of 100 degrees, from 2,500° to 2,400° (which readily results from unskilful firing) will reduce the amount of heat transferred by radiation by 12 per cent. This shows the importance of maintaining the boiler furnace fires in a state of the brightest incandescence for efficient utilization of the available heat of the fuel.

TRANSMISSION OF HEAT THROUGH A BOILER PLATE

It is now possible to construct a picture of what happens when a stream of hot combustion gases heats a boiler tube. (See Fig. 17.)

The boiler shell or tube does not consist merely of a plate of mild steel. The surface adjacent to the hot gases (the gas side) is covered with a layer of soot and oxide of iron, and on the vapour side (the water side) by a thin layer of boiler scale. Both the layer of soot and oxide of iron and the layer of boiler scale are relatively poor conductors of heat.

The heat of the combustion gases is transmitted to the layer of soot and oxide by radiation from the hot gases, and by convection from the flowing gases. At the surface of the boiler tube the gas directly in contact with the layer of soot and oxide is virtually stagnant by reason of the resistance to the gas flow offered by the layer. Heat must therefore be transmitted across this stagnant film of gas by conduction; but gases are poor conductors of heat, so the film offers considerable resistance to the flow of heat. This resistance is quite out of proportion to the thickness of the film.

Having passed through the film of stagnant gas, the heat is to be conducted through the layer of soot, etc., a layer that is also a poor conductor of heat. It passes on through the boiler plate itself, a good conductor, and then meets the second poorly-conducting layer, that made up of the scale. It then passes into the water where boiling and conversion into steam takes place.

This leads to the concept of a *fouling factor* or *dirt factor*, equivalent to a lowering of heat transfer coefficient. This factor is of much practical use in computing heating surfaces.

When the water is boiling at a given pressure, as the temperature difference between the outer heating surface and the water increases, the heat flux increases also, at first slowly and then more rapidly, going through a maximum and subsequently decreasing again as the inner surface becomes to some extent insulated by a poorly conducting volume of water vapour. Heat transmission on the water side must therefore be influenced by convection conditions and established by the character of the water circulation; here a *film factor* on the water side of the plate comes into operation. (See page 166.)

In comparing the performances of different types of boiler and in investigating conditions in any one boiler, the individual layers of media more or less resistant to the heat flux cannot be considered independently, because the temperature differences governing heat transmission in the various layers cannot be known accurately. The heat transfer coefficients indicate the rate of heat flow with a temperature difference of 1 deg. between the hot gas and the boiler plate, on the one side, and the boiler plate and the water in the boiler, on the other. These coefficients are combined with those of the various solid layers, so that an overall heat transfer coefficient is arrived at.

The distribution of heat transmitted from the gases flowing through a boiler at the rate of 6,000 lb. per hour per square foot of area, at two points where the gas temperatures were 1,400° F. and 800° F., respectively, steam pressure 250 lb. per square inch gauge, water and tube temperature about 406° F. is given in Table 9.

TABLE 9

Gas temperature: ° F.	.. .. .	1,400	800
Gas radiation, CO ₂ : B.t.u./sq. ft. hr.	.. .. .	1,340	280
" " H ₂ O: " "	.. .. .	477	107
Total gas radiation	.. .. .	1,817	387
Total rate of heat transfer : B.t.u./sq. ft. hr.	.. .. .	7,660	2,620
Overall heat transfer coefficient: B.t.u./sq. ft. hr. deg. F...	.. .. .	7.7	6.65
Heat transfer by convection (by difference): B.t.u./sq. ft. hr.	.. .. .	5,843	2,233
Convection coefficient : B.t.u./sq. ft. hr. deg. F	.. .. .	5.83	5.66

One of the most complex problems of heat transmission is the evaluation of the performance of a combustion chamber of a furnace or boiler, in which heat is being transmitted simultaneously in all of the ways that have been discussed. Allowance must be made for the combined actions of direct radiation from the flame to the medium heated, the boiler plates or tubes and refractory surfaces, thence back through the flame, with partial absorption therein to the colder evaporation surfaces. Convection and external losses have also to be considered. The problem is beyond the scope of the present treatment, but the considerations involved are dealt with by H. C. Hottel⁹ and Wohlenberg¹⁰ and associates. By the use of the same technique and a knowledge of the rate of fuel consumption and the evaporation of the boiler the distribution of the flow of heat can be traced throughout the boiler system.

HEAT TRANSMISSION IN ECONOMISERS

An economiser is a device for using the sensible heat in the waste gases leaving a boiler furnace to pre-heat the water entering the boiler. The mode of heat transmission is that of a counter-flow heat exchanger in which a balance has to be reached between the rise in temperature of the water and the fall in temperature of the boiler outlet gases. The amount of heat exchanging surface allowed for in the past in the design of conventional economisers has been such as to ensure that there would be no risk of generating steam within the economiser. In recent years, however, steaming types of economisers have come into use; the limitation against the risk of steam production within the economiser naturally does not apply to such types.

It has been shown in the discussion of heat transfer by convection (the predominant means of heat transfer in economisers) from gases at low temperatures that increase of gas velocity is necessary to increase rates of heat transfer. In the older installations velocities had to be kept low in order to limit loss of draught due to the resistance of the tubes, and a large heating surface or a large number of tubes was required for any specific duty; this was because only natural (chimney) draught was available. The efficiency of the heat transfer through the surface of the tubes was preserved because they were regularly scraped clean.

Better heat transfer by increased velocity has been effected by modifying the design, e.g. as in the vertical type of apparatus and by the use of baffles. In a particular case the use of baffles was shown to increase the heat transfer coefficient from 3 B.t.u./sq. ft. hr. deg. F. to 5.5-7.7. Higher velocities tend to keep the tubes cleaner; the limit in the development of the velocity of the gases depends upon the available draught and the additional power to be provided where forced draught is employed.

It is not correct to say, however, that a higher draught loss necessarily means a greater rate of heat transfer unless it is clearly understood that the form, type and arrangement of the heating surface all remain constant. Further, the question of fan power involves economic considerations outside the heat transfer problem.

A related question may also be examined, viz., does the staggering of the

tubes of an economiser confer any appreciable benefit? Here the generalization that staggered tubes are better than non-staggered breaks down. The pitching of the tubes in an economiser, say $4\frac{9}{16}$ inches diameter on 8-inch centres is so wide and the gas velocities in general are so low that the increase in both heat transfer and draught loss is quite negligible. The point has been subjected to lengthy examination, and the modern method for speeding up rate of gas travel in certain types of economisers is to arrange the tubes in groups with vertical baffles between, so that instead of being across them, as in the normal arrangement, the flow of gases is approximately parallel to the length of the tube. Thus, in an economiser of say 192 tubes, arranged in 24 rows of eight 9-ft. tubes, the area for cross gas flow is 33.5 square feet. If this economiser is arranged in three groups of 64 tubes each, with vertical baffles between, the gas flow area becomes 23.18 square feet and with the same total gas quantity the gas speed is proportionately greater.

Both heat transfer rate and draught loss increase, but the latter is not a direct function of the former in this example, since part of the increased loss in draught is due to change of direction over and under the baffles. A typical set of performance figures will illustrate this point (Table 10).

TABLE 10. PERFORMANCE FIGURES FOR AN ECONOMISER

Economiser of 192 tubes (24 × 8) 9 ft. long.
Heating surface 2,234 sq. ft.

	<i>Normal arrangement</i>	<i>In three groups with vertical baffles</i>
Weight of water—lb./hour	20,000	20,000
Weight of gases—lb./hour	45,000	45,000
Gas flow area—sq. ft.	35.5	23.18
Gas velocity—lb./hr sq. ft. of flow area	1.345	1.945
Heat transfer coefficient, B.t.u./sq. ft. hr. deg. F ..	3.5	3.8
Inlet gas temperature—° F.	650	650
Outlet gas temperature—° F.	404	394
Inlet water temperature—° F.	120	120
Outlet water temperature—° F.	244	251
Total draught loss due to friction and change of direction—in. w.g.	0.07	0.24
Draught loss due to change of direction—in. w.g. ..	—	0.08

For this particular set of conditions, therefore, there was a 7 deg. F. rise in water temperature, in return for an extra 0.17 inch w.g. of draught.

How far this gain in performance is justified depends again upon circumstances involving a wide range of considerations, operational and economic. If, for example, induced draught enables an inferior and formerly unusable fuel to be used, some proportion of the fan charges should logically be added to the fuel cost, and not debited entirely to the economiser saving.

The wider aspects of these problems are dealt with in the later chapters on boilers and their auxiliaries. The principles of heat transmission in furnaces are dealt with in Chapter 19.

HEAT LOSSES

In this chapter attention has so far been directed mainly to the second stage of the process of heating, that of transmitting heat to the objects that have to be heated. The third stage, that of preventing the escape of heat in directions where it will serve no useful purpose, is now considered.

Heat can escape as part of the sensible heat of the flue gases or by conduction into the outer air. The loss of heat in the flue gases has been considered in

Chapter 7. The following discussion relates to the loss of heat through furnace walls, through the surface of steam pipes, hot water tanks and in general in any manner in which heat can be dissipated from industrial plant by the processes under discussion in this chapter—convection, conduction and radiation.

If the temperature of part of an industrial furnace is higher than that of the atmosphere, heat will be conducted through the casing or outer wall. This heat will raise the temperature of the outer sides of the wall or casing above that of the atmosphere and its surroundings. The outer surface will then lose heat by convection to the air and by radiation to the surrounding cooler objects.

It is an essential characteristic of this form of heat loss that the quantity of heat conducted through the wall or casing must exactly equal the quantity of heat radiated and convected from the outer surface. If the steady state has not been reached and this condition is not fulfilled, the temperature of the outer surface will change until the condition is fulfilled; at this point the steady state will be set up. Some account of the industrial significance of heat losses in the unsteady state will be found in Chapter 19.

When the steady state has been reached it is thus possible to calculate the surface temperature of the wall. An example of practical value, relating to the insulation of a furnace, will make the methods of calculation clear. (See also pages 155-7).

HEAT LOSSES FROM SURFACES

The total of the heat losses by radiation and convection is obtained by a combination of Equations 8 and 37.

$H_c + H_r = C(t_1 - t_2)^{1.25} + 17.13 \times 10^{-10} \times \epsilon(T_1^4 - T_2^4)$, B.t.u./sq. ft. hr. (42)

The temperature of the hot surface is governed not only by the character of the heat loss from the external surface, but also by the heat flux through the mass forming the wall.

The calculated values of the combined radiation and convection loss from a furnace wall in a still atmosphere at 70° F. are shown¹¹ in Table 11.

TABLE 11

Surface temp. ° F.	Heat loss in B.t.u./sq. ft. hr.		
	Vertical surface	Horizontal surface	
		Facing upward	Facing downward
100	48	54	41
150	152	172	128
200	280	316	236
250	436	494	360
300	618	696	526
350	828	928	708
400	1,070	1,190	930
450	1,360	1,510	1,190
500	1,680	1,850	1,480
550	2,050	2,250	1,810
600	2,470	2,700	2,200
650	2,940	3,200	2,640
700	3,480	3,770	3,140
750	4,050	4,370	3,680

Table 11 is based on the coefficient of emissivity, ϵ , for firebrick (Table 6), and would require to be recalculated if the material with which the wall was

coated had a different coefficient of emissivity. Actually the governing factor in determining heat losses through furnace walls is the insulating character of the wall.

The effect of the coefficient of emissivity of the material is shown in Fig. 19. By using a bright unscratched metal surface the value ϵ can be reduced to about 0.05 (cf. Table 6) and the heat loss by radiation becomes very small.

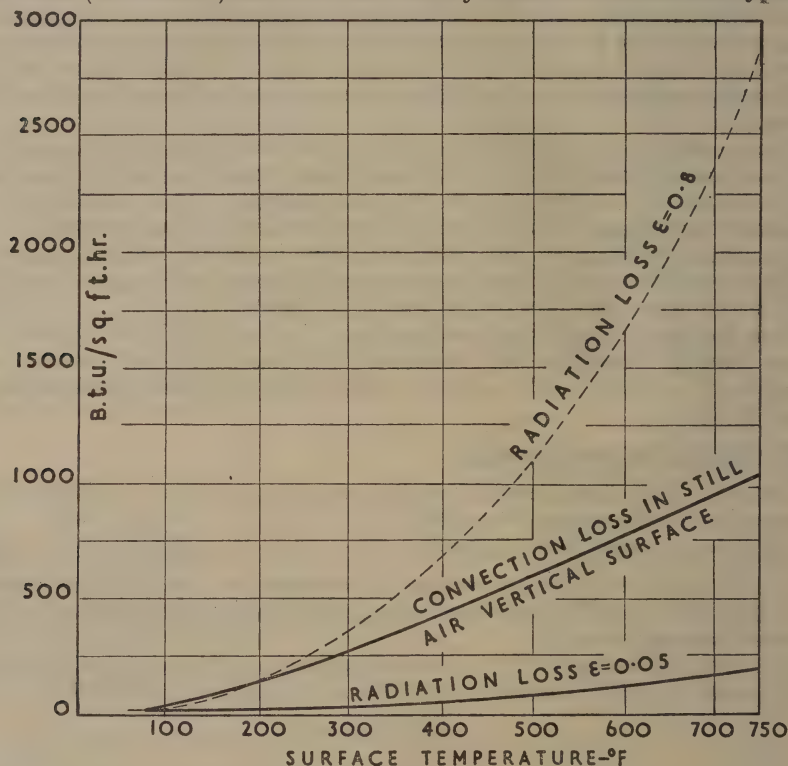


FIG. 19. Convection and radiation losses from surfaces in still air at 70°F

This principle is employed in hospitals and other places where it is possible to maintain the surface in something approaching its initial bright condition. The heat loss by convection, however, remains.

The convection loss for the same temperature conditions is greatly affected by air currents.

Table 12 gives an estimate¹² of the amount of heat transfer in moving air from a vertical surface ($\epsilon=0.9$) maintained at various temperatures, the air being at 70° F.

TABLE 12. HEAT LOSS FROM FURNACE WALL IN AIR MOVING AT 15 M.P.H.

Temp. of Surface ° F.	B.t.u./sq. ft. hr. Air moving at 15 m.p.h.		
	Radiation	Convection	Total
100	30	162	192
200	169	700	869
300	390	1,240	1,630
400	715	1,780	2,495

The importance of properly housing furnace structures, hot water tanks, etc., and of ensuring that their outer surfaces are not subjected to draughts will be seen from this table.

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CHAPTER 10

THE FLOW OF FLUIDS

AND THE MEASUREMENT OF STEAM, WATER, GAS AND AIR

FLUID FLOW is a highly important branch of fuel technology. Liquids, vapours—including steam—and gases have to be transported in pipes, an operation involving the expenditure of power, and it is necessary to know the principles of fluid flow in order to design the plant efficiently. Furnace gases flow through mains and chambers of many sizes and shapes. As the heating of a furnace and of the stock contained in it depends on the correct flow of the hot gases, a knowledge of the pressure variations in these systems is essential at the design stage. From special studies of fluid flow, furnace draught may be calculated or efficient convection heating planned.

THE MECHANICS OF FLOW

The energy per unit mass (say one pound) of a fluid is made up of three parts: (a) potential energy due to its height above some zero level or datum line, (b) kinetic energy due to its velocity and (c) pressure energy due to the absolute pressure on the fluid. In foot-pound-second units these are:

(a) potential energy .. H ft.lb./lb., (b) kinetic energy $\frac{V^2}{2g}$ ft.lb./lb. and

(c) pressure energy .. $144 \frac{P}{w}$ ft.lb./lb.

where H is height above datum line — ft.,

V is velocity of flow—ft./sec. w is the specific weight of fluid—lb./cu.ft.

P is the absolute pressure—lb./sq.in. and g is a constant—32.17.

It should be noted that the term *pound* is used either as a unit of force or as a unit of mass, since pressure, P , is defined as force per unit area and density, ρ , as mass per unit volume. It is therefore important to distinguish between the density, ρ , of a fluid expressed as lb. (mass)/cu. ft. and its specific weight, w , expressed as lb.(weight)/cu.ft. These are *numerically* equal but relate to different physical quantities.

In the expression (c), the factor 144 is necessary because the pressure, P , is expressed as lb./sq.in., not lb./sq.ft. All three expressions are correct only if we assume that the datum line is on the earth's surface and that 'g' remains constant at all points on the earth's surface.

The condition illustrated in Fig. 1 may now be considered. This shows a constant level tank with a vertical outlet pipe that can be closed by a valve at its lower end. If the valve is closed, a pressure gauge in the position shown in the diagram will give the reading P lb./sq.in. We thus have

$$H = 144 \frac{P}{w} \text{ or } 144P = Hw.$$

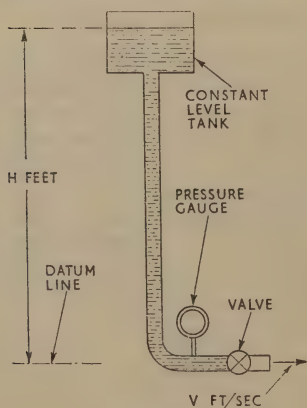


FIG. 1

The height H is usually called the *head of liquid*. If the valve is opened, the pressure on the gauge becomes substantially zero and the liquid flows down the pipe at velocity V ft./sec. Since this velocity has been acquired because

of the fall of the liquid through a height H (assuming there has been no frictional loss in the pipe) we can say that the whole of the potential energy has been converted into kinetic energy and therefore, that H equals $\frac{V^2}{2g}$. This is the head necessary to impart a velocity V , and $\frac{V^2}{2g}$ is known as the *velocity head*. The pressure corresponding to H is $144P$ lb./sq. ft. This equals wH , i.e. $\frac{wV^2}{2g}$, the *velocity head pressure*.

The law of conservation of energy requires that if unit mass of fluid changes position or velocity, and if no energy is imparted to it or lost from it (e.g. by friction), the change in total energy must be zero.

Thus in Fig. 2, since the pressure and velocity at the free surface are both zero and the free surface is H_0 ft. above the datum line

$$\text{total energy} = H_0 = H_1 + \frac{V_1^2}{2g} + 144 \frac{P_1}{w} \dots \dots \dots (1)$$

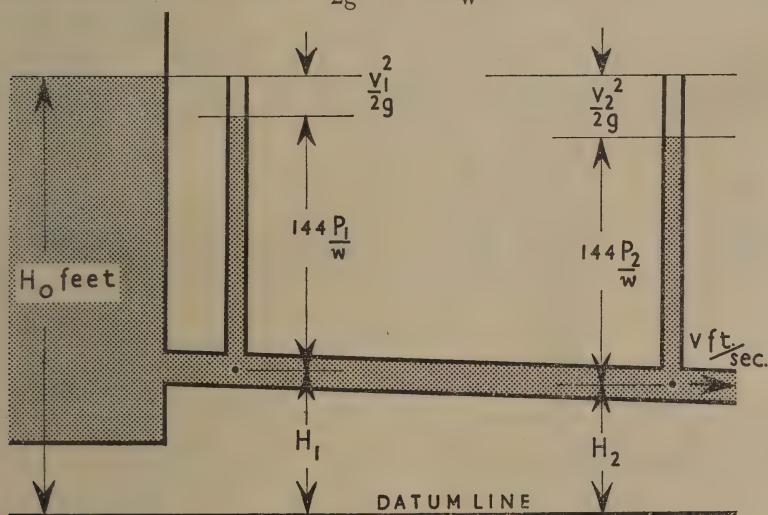


FIG. 2

If suffix 1 applies to the first stage of the unit mass of fluid and suffix 2 to the second stage, then allowing for any change of specific weight and any change in velocity due to variation in section:

$$\left[H_2 + \frac{V_2^2}{2g} + 144 \frac{P_2}{w_2} \right] - \left[H_1 + \frac{V_1^2}{2g} + 144 \frac{P_1}{w_1} \right] = 0 \dots (2)$$

If the fluid is incompressible, $w_1 = w_2 = w$, and the equation becomes simplified to

$$\left[H_2 + \frac{V_2^2}{2g} + 144 \frac{P_2}{w} \right] - \left[H_1 + \frac{V_1^2}{2g} + 144 \frac{P_1}{w} \right] = 0 \dots (3)$$

Equation 3, commonly called Bernoulli's Equation, is a restricted form of Equation 2, and is applicable to the flow of liquids, or of gases when the pressure difference ($P_2 - P_1$) is small (less than 5 per cent. of the pressure P_1), that is, when the gas density is sensibly constant. The equations given from now on are derived from Equation 3, i.e. they apply to an incompressible fluid. (The derivation of flow equations for compressible fluids starting from Equation 2 is complicated and is not considered here.)

Equation 3 applies to a frictionless fluid; with a real fluid there will be the

losses of energy due to friction. Furthermore, energy may be imparted to the fluid by means of a pump or compressor. In practice we may extend Equation 3 to take these factors into account. Expressing the result in words:

The increase in energy per unit mass of fluid *plus* the energy lost by friction equals the energy added by the pump, or, using symbols,

$$\left[H_2 + \frac{V_2^2}{2g} + 144 \frac{P_2}{w} \right] - \left[H_1 + \frac{V_1^2}{2g} + 144 \frac{P_1}{w} \right] + 144 \frac{\Delta P}{w} = 144 \frac{\Delta P_p}{w} \quad (4)$$

ΔP is the pressure (lb./sq.in.) necessary to overcome the friction, and ΔP_p (lb./sq.in.) is the pressure increase across the pump. Equation 4 may be re-arranged as follows:

$$w(H_2 - H_1) + \frac{w}{2g}(V_2^2 - V_1^2) + 144(P_2 - P_1) + 144\Delta P = 144\Delta P_p \quad (5)$$

A practical system is illustrated in Fig. 3 in which a pump is shown drawing liquid from a tank open to the atmosphere and sending it to a storage vessel located at a different level, and maintained under pressure. The pressures at the various points are shown in lb. per sq. in. absolute, i.e. gauge pressure *plus* atmospheric pressure at the point where the gauge is situated. Atmospheric pressure may usually be assumed constant and equal to 14.7 lb./sq.in.

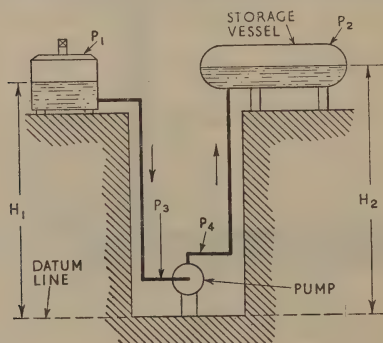


FIG. 3

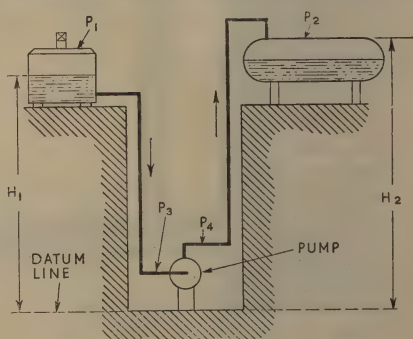


FIG. 4

ΔP_p is $P_4 - P_3$ and at the free surfaces the velocities V_1 and V_2 are sensibly zero. It is easily seen that if both ends of the system are open to air $P_2 - P_1$ is zero; and if the free surfaces at the two ends of the system are at the same level $H_2 - H_1$ is zero.

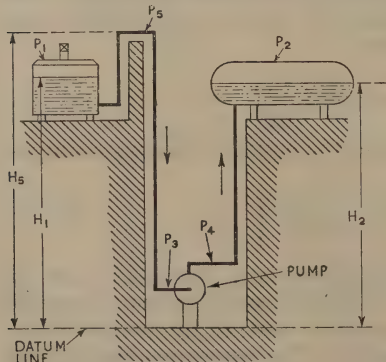


FIG. 5

If the discharge into the receiving tank is above the liquid surface, then the end of the pipe becomes the free liquid surface, and H_2 is the height of this point, as in Fig. 4. Here V_1 may be neglected but V_2 will be the discharge velocity from the pipe.

A point of great practical importance is illustrated in Fig. 5. After leaving the tank and before reaching the pump, the pipe rises in order to clear an obstacle. We can apply Equation 5 between *any*

two points in the pipe. Thus between the points 1 and 5 on Fig. 5 we get:

$$w(H_5 - H_1) + \frac{w}{2g}(V_5^2 - V_1^2) + 144(P_5 - P_1) + 144\Delta P = 0 \quad (6)$$

ΔP_p is equal to zero, since the pump is not included in the section of line dealt with. The pressure necessary to overcome friction between the tank and point 5 is $144\Delta P$. Equation 6 can be rewritten as follows:

$$144 P_5 = 144 P_1 - w(H_5 - H_1) - \frac{w}{2g} (V_5^2 - V_1^2) - 144\Delta P \quad \dots \quad (6a)$$

$(H_5 - H_1)$ is obviously positive, as is $(V_5^2 - V_1^2)$, so that P_5 will be negative if $\left[w(H_5 - H_1) + \frac{w}{2g} (V_5^2 - V_1^2) + 144\Delta P \right]$ is greater than $144P_1$. The system may fail to work as H_5 is increased because P_5 is an absolute pressure and cannot be less than zero. In the phrase frequently used, the pump is "pulling a vacuum" at point 5, and the system will fail to work if the vacuum required to get the liquid "over the hill" is greater than the pump can generate, or, alternatively, if it is so great that the liquid being pumped boils at the low pressure generated. The system can also fail if the diameter of the suction line to the pump is small, or if the pipe is throttled by a partly closed valve, so that ΔP is large; the point of danger may be at the inlet to the pump. This stresses the need to apply Equation 5 to more than one part of the system if positions of low pressure, e.g. at P_5 , are present. These extra calculations are not necessary if the pump is installed with a short suction line of ample diameter, and with no rise—a condition to be fulfilled wherever possible.

So far the pumping of a liquid has been discussed, but in practice the fluid may be a gas, such as air or some other gas being forced through a pipe by a blower or a compressor, or flue gas flowing through a furnace under the convective forces such as the pull of a chimney. Equation 5 is applicable to such cases as long as the pressure drop between the two points being considered is small compared with the absolute pressure, i.e. as long as $P_2 - P_1$ is less than 5 per cent. of P_1 . This case of gas flow with low pressure drop is the common one. The equations for the more complicated case of high pressure drop when changes in density occur cannot be neglected are given on page 208.

When making calculations on the flow of gas in a system including a compressor or a throttling valve or any other device giving a large change in pressure, the calculation must be done in two stages, first on the suction side of the compressor, or the high pressure side of the valve, and then on the down-stream side; Fig. 12 illustrates the practical application of this.

In making pressure drop calculations for gas flow the term $w(H_2 - H_1)$ in Equation 5 can often be neglected, owing to the low density of gases (compared with liquids) but there is one very important exception to this statement, namely the calculation of the flow of gas through a furnace with its associated stack. In this case, which is considered in detail on page 212, there is no fan to force the gas along; the pressure difference producing flow can be derived from the application of Equation 5, and depends on the tendency of the hot gas to rise inside the stack because its density is less than that of the surrounding air.

The discussion so far has emphasised the terms $w(H_2 - H_1)$ and $144(P_2 - P_1)$ in Equation 5. In certain circumstances it will be a simple matter to allow for the term $\frac{w}{2g} (V_2^2 - V_1^2)$. For example, when calculating the pressure drop between two points in a pipe of uniform diameter for an incompressible fluid, V_2 and V_1 are equal, so this term is zero. If the pressure drop between a feed tank containing a liquid and a point in a pipe is calculated, V_1 will be zero, and the term becomes $\frac{wV_2^2}{2g}$. In most cases the calculation is made between one large vessel and another, so that V_2 and V_1 are both zero, and the term is not considered. There is a loss of energy in such cases due to the speed of the

fluid as it discharges from the pipe into the receiving vessel. This loss is akin to the $(V_2^2 - V_1^2)$ term, being also a loss of kinetic energy, but in this chapter it is allowed for when calculating $144\Delta P$. The reader is advised therefore to neglect the term $\frac{w}{2g}(V_2^2 - V_1^2)$ as a general rule, and to assume that, except in special cases, where its magnitude will be fairly obvious, either it is negligibly small or its effect has already been allowed for when assessing the term $144\Delta P$.

Treating equation 5 in this manner we get

$$w(H_2 - H_1) + 144(P_2 - P_1) + 144\Delta P = 144\Delta P_p \quad . \quad . \quad (7)$$

and of these terms only ΔP is subject to any difficulty.

ΔP is the pressure difference (lb./sq.in.) necessary to force the fluid through the pipe system or duct, including all its fittings such as valves, bends, etc., if this system is laid out horizontally. It also includes any pressure drop or pressure losses necessary to get the fluid in and out of the pipe. It is, therefore, made up of three parts:—

- (a) the pressure drop due to friction when the fluid is flowing through a straight horizontal pipe of the given diameter, the length of the pipe, L , being the actual length of the pipe measured along the centre line with the fittings in position;
- (b) the additional pressure drop due to increased resistance produced by the fittings;
- (c) the entrance and exit losses, the former being due to a small increase in friction over the initial length of the pipe caused by the extra disturbance of the fluid as it enters, and the latter being accounted for by the loss of the kinetic energy with which the fluid leaves the pipe.

These three quantities are dealt with below, the most important calculation being that of the friction loss in the straight horizontal pipe or duct.

FLOW EQUATION FOR A PIPE

The equation for calculating the pressure drop for a liquid flowing in a straight horizontal pipe is derived as follows. In order to keep the equation in *self-consistent units*, pressures are expressed in poundals per square foot, and the density ρ as pounds (mass) per cubic foot.

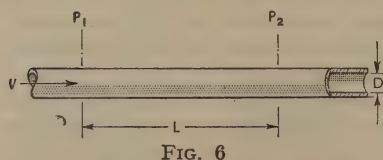


Fig. 6 shows a pipe of length L and diameter D , in which the liquid is flowing with velocity V , with a pressure drop $P_1 - P_2 = \Delta P$.

The frictional force per unit area of the pipe wall is assumed to be τ .

The *mean* linear velocity, V , is the volume rate of flow divided by the cross-sectional area of the pipe. The assumption is made that the liquid is moving with velocity V over the whole cross section. Actually this is far from true, particularly in streamline flow: but the assumption does not affect the practical usefulness of the equations. The true velocity distribution over the cross-section is discussed below. (page 205).

The energy lost in unit time as the result of the pressure drop is

$$(P_1 - P_2) \times (\text{volume of fluid per unit time}), \text{ i.e. } (P_1 - P_2) \times \frac{\pi D^2 V}{4}.$$

The energy lost in friction is the total force multiplied by the distance travelled in unit time, or $\tau \times (\text{wetted area}) \times V$, or $\tau \pi D L V$.

These two energies must be equal,

i.e. $(P_1 - P_2) \times \frac{\pi D^2 V}{4} = \tau \pi D L V \therefore P_1 - P_2 = \Delta P = 4 \tau \frac{L}{D}$

Mathematicians designate an absolute pressure as P and a difference in pressure as ΔP . In this chapter ΔP means the pressure difference between two points in the system being considered; it is this that has to be overcome by a pump or a natural pressure head.

It has been found from experience that the most important variable affecting the value of ΔP is the change in kinetic energy; this is usually put into the equation in the form $\frac{\rho V^2}{2}$ i.e. the kinetic energy per unit volume.

Introducing this term gives the equation

$$\Delta P = 8 \left(\frac{\tau}{\rho V^2} \right) \frac{L}{D} \frac{\rho V^2}{2}$$

Substituting f , for the expression $8 \left(\frac{\tau}{\rho V^2} \right)$,

$$\Delta P = f \frac{L}{D} \frac{\rho V^2}{2} \quad \dots \dots \dots (8)$$

The factor f is known as the *friction factor*, and the means of determining its value, and thus calculating ΔP , are given below (*Determination of Friction Factor*, page 204). If D and L are in feet, V is in ft./sec. and τ is in poundals/sq.ft. Equation 8 gives the pressure drop in poundals per square foot. It is usual to designate pressure drops in pounds per square foot, or per square inch; by this is meant pounds (force) though the word "force" is not usually expressed. To convert from poundals to pounds we must divide by the local value of g^* , the acceleration due to gravity and, to keep the units consistent replace ρ (density) by w (specific weight — sp. wt.). This gives the equation

$$\Delta P \text{ (lb./sq.ft.)} = f \frac{L}{D} \frac{w V^2}{2g} \quad \dots \dots \dots (9)$$

This, known as Fanning's Equation, can be alternatively expressed for use with the units adopted in this chapter, namely: ΔP in pounds per square inch; D in inches and L in feet; V in feet per second and w in pounds per cubic foot, and in Britain it is sufficiently accurate to adopt the standard value of g , viz. 32.174.

Thus $\Delta P = 1.295 \times 10^{-3} \frac{f L w V^2}{D} \text{ lb./sq.in.} \quad \dots \dots \dots (10)$

FLOW EQUATION FOR NON-CIRCULAR DUCTS

Equation 10 applies for the flow in a pipe of circular cross section. If the pipe or duct has any other shape the following equation applies:

$$\Delta P = 1.295 \times 10^{-3} \frac{f L w V^2}{4M} \quad \dots \dots \dots (11)$$

where M is the hydraulic mean depth, and is equal to the cross-sectional area of the duct divided by the wetted perimeter.

In the case of a circular pipe running full $M = \frac{\pi D^2}{4} \div \pi D$ i.e. $\frac{D}{4}$ and it can easily be seen that Equation 11 will convert to Equation 10.

* By international agreement a standard value of $g = 32.174 \text{ ft./sec}^2$. has been adopted. This value may be used in place of the local value of g in the British Isles with accuracy greater than that of most engineering measurements.

Values for M for some common cross sections running full are:

Square duct of side a :
$$M = \frac{a^2}{4a} = \frac{a}{4}$$

Oblong section, $a \times b$:
$$M = \frac{ab}{2(a+b)}$$

Annulus, large diameter D ,
small diameter d :
$$M = \frac{\pi 4(D^2 - d^2)}{\pi(D+d)} = \frac{D-d}{4}$$

VISCOSITY

A liquid which flows with difficulty is generally said to be viscous, and the property that determines the internal resistance to flow is its *viscosity*.

Resistance to fluid flow is caused by friction. Friction in solids is a force exerted between surfaces in contact. Fluids in motion are in contact with the surfaces of the pipes or ducts in which they move, but the layer of fluid in immediate contact with a surface is stationary so that the force acting between solid surfaces in contact does not operate in the same way between moving fluids and the surfaces by which they are bounded.

Particles of moving fluids do not move with uniform velocity throughout the whole area of a pipe or duct. (See p. 205.) Immediately against the surface there is the stationary layer, perhaps only one molecule thick. The work of Langmuir suggests that the first layer may be bound to the surface by physico-chemical forces. Subsequent layers move with a velocity which increases with their distance from the surface. The work to be expended in order to produce this relative motion represents frictional forces that come into play in the interior of the liquid. This force tends to retard the more rapidly moving layers and to accelerate those that are moving less quickly. The force required to cause the relative motion under standard conditions is known as *viscosity*.

The magnitude of the viscosity may be defined as the force expressed in dynes, acting on an area of 1 square centimetre, necessary to produce a difference of velocity of 1 centimetre per second between a layer of fluid and a parallel layer 1 centimeter distant. Thus in Fig. 7, if the layer of fluid AB

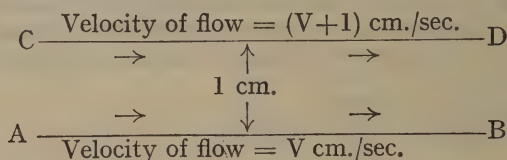


FIG. 7. Illustration of the principle of viscosity.

moves with a velocity V cm./sec. and the layer CD moves with a velocity of $V+1$ cm./sec., the force in dynes per square centimeter acting on the layer CD just sufficient to cause this difference of motion is the *coefficient of viscosity*. In c.g.s. units this unit is known as the *poise*.

In f.p.s. units, the coefficient of viscosity is the force in *poundals* which, acting on an area of 1 square foot, will produce a differential velocity of 1 foot per second between two parallel layers of fluid 1 foot apart. There is no name for the f.p.s. unit. Numerically,

$$\text{viscosity in poises} \times 0.0672 = \text{viscosity in f.p.s. units.}$$

$$\text{viscosity in f.p.s. units} \times 14.88 = \text{viscosity in poises.}$$

These are units of "absolute" viscosity, and usually designated by the Greek letter, η .

It is often convenient to use a quantity known as *kinematic viscosity*, commonly designated by the Greek letter ν . In the c.g.s. system the unit of kinematic viscosity is the *stoke*.

Kinematic viscosity is $\frac{\text{absolute viscosity}}{\text{density}}$

Both the viscosity and density must be expressed throughout in the same units system.

i.e. stokes = $\frac{\text{poises}}{\text{gm./c.c.}}$

or in f.p.s. units = $\frac{\text{f.p.s. units of absolute viscosity}}{\text{lb./cu. ft.}}$

Kinematic viscosity in stokes $\times 0.0010764 = \text{f.p.s. units.}$

Kinematic viscosity in f.p.s. units $\times 929.03 = \text{stokes.}$

In practice the smaller units, the centipoise ($\frac{1}{100}$ poise) and the centistoke ($\frac{1}{100}$ stoke) are commonly used. (See table, page 203.)

In oil technology viscosity is commonly measured in terms of the time taken for a standard quantity of the oil to pass through a standard orifice under standard conditions. The viscosity is then expressed in seconds of time. (See Chapter 30.)

It is generally true that viscous liquids become 'thinner' when heated; they flow more readily. This means in practice that less force is required to overcome the internal friction. For liquids, therefore, viscosity becomes less as the temperature rises. In gases, however, the opposite occurs: the viscosity becomes greater as the temperature rises. This fact is not always appreciated. Its practical significance is that more fan power is required to move gases at higher temperatures. Thus in supplying pre-heated gases to burners, both the greater frictional resistance produced by the expansion of the heated gases and the effect of the increased viscosity have to be overcome.

Viscosity changes rapidly with temperature. Thus kinematic viscosity must always be calculated with reference to the viscosity and density of the fluid at the temperature concerned, a matter of great importance in all problems connected with the flow of fluids. At pressures reasonably near atmospheric, even up to (say) 100 lb./sq.in., viscosity may be regarded as independent of the pressure.

No general law can be given regarding the effect of temperature on the viscosity of liquids. Experimentally determined values must be used. In Table 1 are given some values for water; intermediate values can be obtained by interpolation. Those for fuel gases are given in Tables 2 and 3.

TABLE 1. VISCOSITY OF WATER

Temperature		Absolute viscosity, η		Kinematic viscosity, η	
°C.	°F.	Poises	f.p.s. units	Stokes	f.p.s. units
0	32	0.01792	0.001204	0.01792	0.00001930
10	50	0.01308	0878	0.01308	1407
15	59	0.01140	0766	0.01141	1228
20	68	0.01005	0675	0.01007	1084
30	86	0.00801	0538	0.00804	0866
50	123	0.00549	0369	0.00556	0599
70	158	0.00406	0273	0.00415	0447
100	212	0.00284	0191	0.00296	0319

TABLE 2

ABSOLUTE VISCOSITY OF INDUSTRIAL FUEL GASES IN c.g.s. UNITS (POISES) *

Type of gas	Blast furnace gas	Coke oven gas debenzolised	Continuous vertical retort gas (steaming)	Mechanical producer gas		Blue water gas	Steam	Air
				Coal	Coke			
Density at 0° C. and 760 mm.	0.0013	0.00049	0.00062	0.00113	0.00116	0.000712	0.000804	0.001293
Temp.	Absolute viscosity in poises $\times 10^6$ (See Note c.)							
0° C.	160	114	132	163	166	153	88	170
20	170	121	140	172	176	162	95	180
40	179	128	148	181	185	171	103	190
80	196	141	162	198	203	187	118	209
120	214	153	177	215	220	203	135	225
160	230	166	191	231	236	217	152	242
200	245	177	204	248	252	231	167	258
250	263	190	219	263	270	248	186	276
300	280	203	233	280	287	264	203	295
400	312	227	261	312	319	293	238	329
500	342	249	285	341	349	321	272	359
C ¹	405	423	416	393	394	392	950	397

(a) Densities in gm./c.c. at 0° C. and 760 mm.

(b) To obtain values for density in lb./cu. ft. at 32°F. and 29.92 in. bar., multiply by 62.428.

(c) To obtain absolute viscosity in poises divide the values here given by 10^6 .

TABLE 3. KINEMATIC VISCOSITY OF INDUSTRIAL FUEL GASES IN C.G.S. UNITS (STOKES) AT ATMOSPHERIC PRESSURE *

Type of gas	Blast furnace gas	Coke oven gas debenzolised	Continuous vertical retort gas (steaming)	Mechanical producer gas		Blue water gas	Steam	Air
				Coal	Coke			
Temp.								
0° C.	0.123	0.233	0.213	0.144	0.143	0.217	0.109	0.131
20	0.141	0.264	0.242	0.164	0.162	0.246	0.128	0.152
40	0.159	0.298	0.274	0.184	0.182	0.276	0.147	0.172
80	0.197	0.371	0.338	0.228	0.226	0.342	0.191	0.212
120	0.238	0.449	0.411	0.275	0.272	0.412	0.240	0.254
160	0.282	0.535	0.489	0.325	0.322	0.488	0.295	0.300
200	0.328	0.622	0.570	0.378	0.374	0.567	0.356	0.346
250	0.390	0.740	0.676	0.448	0.444	0.672	0.436	0.413
300	0.455	0.866	0.789	0.523	0.517	0.783	0.528	0.480
400	0.595	1.136	1.037	0.681	0.676	1.023	0.730	0.628
500	0.749	1.437	1.300	0.857	0.850	1.280	0.963	0.787

*Absolute viscosities in Table 2 are calculated from the modified Sutherland Formula.

$$\eta_t = \frac{\eta_0}{1 + t/C^1} \times \left(\frac{273 + t}{273} \right)^{\frac{3}{2}} \text{ where } \eta_t \text{ and } \eta_0 \text{ are viscosities at } t^\circ \text{ C. and } 0^\circ \text{ C. respectively.}$$

Kinematic viscosities in Table 3 are derived from values of absolute viscosity, as thus calculated, by dividing by the density at the corresponding temperature.

STREAMLINE AND TURBULENT FLOW

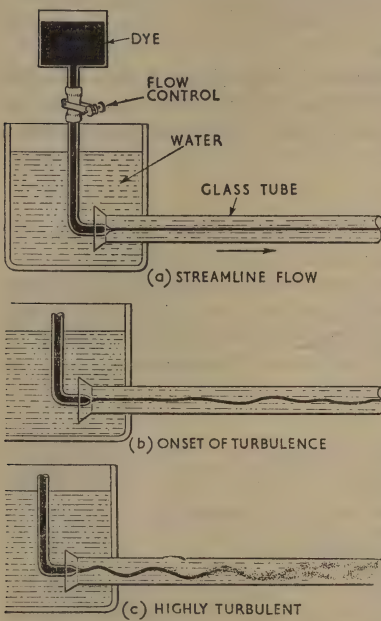


FIG. 8

The flow of a fluid may be either streamline or turbulent. In the former type of flow the molecules may be regarded as moving in an orderly manner following a path parallel to the axis of the tube; whereas in turbulent flow the liquid in the tube is a mass of eddies, and as a result the path followed by a particle is wavy. It is not usually possible to see the eddies, but they can be made visible in the case of a clear liquid, such as water flowing through a glass tube, if arrangements are made to introduce a thin stream of dyed liquid into the tube. The appearance of a tube in which the flow is made visible in this way is shown in Fig. 8, a, b, and c.

Investigations to ascertain the factors governing the change from one type of flow to another have shown that for all sizes of tubes, velocities and fluids (both gases and liquids), the character of the flow is determined solely by the value of an expression called the *Reynolds' Number* (Re), after Osborne Reynolds who made the first experiments of this kind (see also Chapter 9).

The Reynolds' Number is defined by the expression $Re = \frac{VD}{\nu} = \frac{VD\rho}{\eta}$ where ν is the kinematic viscosity of the fluid and η the absolute viscosity. Viscosities of liquids and gases are given in the literature in both forms, but it will generally be found that for liquids they are given as kinematic viscosity, and for gases as absolute viscosity.

The expressions $\frac{VD}{\nu}$ and $\frac{VD\rho}{\eta}$ are dimensionless. *Consistent units must, however, be used*; for instance, V in cm./sec. and D in cm. ν in Stokes (poises divided by gm./c.c.). The following units are adopted in this chapter and a conversion factor is necessary in evaluating Reynolds' Numbers, as shown in the following table:

Quantity	Units in this chapter	Factors for Conversion to consistent units
Velocity (V)	ft./sec.	1
Diameter (D)	inches	0.083
Kinematic viscosity .. (ν)	centistokes	0.00001076
Absolute viscosity .. (η)	centipoises	0.000672
Density (ρ)	lb/cu.ft.	1

By combining these factors, the Reynolds' Number for a round pipe is $7,742 \times \frac{VD}{\nu}$ or $124 \times \frac{VD\rho}{\eta}$. For channels of other shapes, D is replaced by $4M$.

When calculating Re for a gas, it is to be noted that V changes along the pipe as the pressure falls, and Re would appear to vary. However, the absolute

viscosity of the gas, η , and the product $V\rho$ are unaffected by pressure; thus the Reynolds' Number will still be independent of pressure. Its value may be calculated from the velocity and the density at any point in the pipe, the point usually chosen being either of the two ends.

If Re is below 2,000 the flow may be streamline; if it is above 3,000 the flow will be turbulent. The change from one type to the other occurs gradually as the Reynolds' Number increases between these values, and this region of flow is called the *critical region*.

Determination of Friction Factor, f

In addition to enabling the character of the flow to be predicted, the Reynolds' Number is of value for determining the friction factor f .

The relation between the Friction Factor, f , and Re , for smooth pipes, is as given by curve A in Fig. 9. This, and the other curves in Fig. 9, have been derived experimentally. By plotting f against the non-dimensional number Re in this manner, the curve A has a general application to fluids flowing in pipes and is not restricted to a particular pipe size or flow rate.

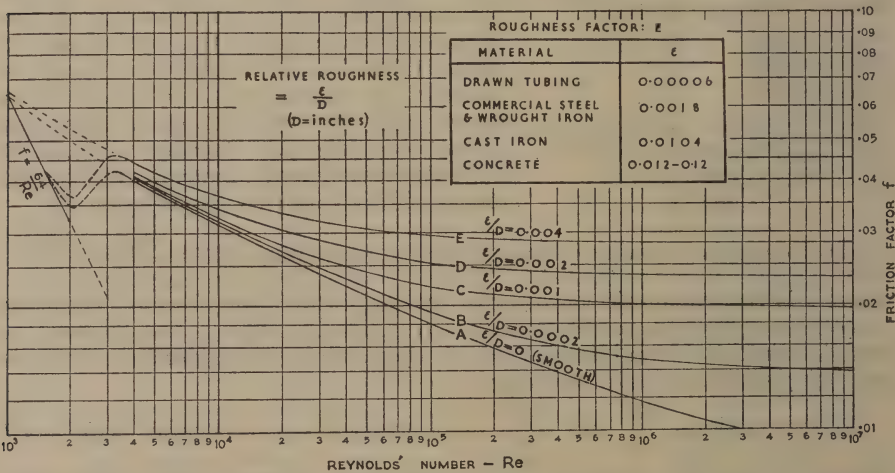


FIG. 9. Relation between Reynolds' No., Re , and Friction Factor, f .

For rough pipes it is necessary to calculate a *relative roughness factor*, the ratio ϵ/D , where ϵ is the *roughness factor* and D is the diameter in inches (see Fig. 9). The curves for rough pipes have likewise a general applicability.

When the relative roughness factor is found to lie between two curves it is always advisable to use the higher curve, this procedure ensuring that some allowance is made for fouling of the pipes during use. When heavy fouling is expected reference should be made to more comprehensive tables in the literature.

From Fig. 9 the streamline, critical and turbulent regions can easily be distinguished. On the left is a single straight line that can be continued beyond the diagram to the lowest values of Re ; this gives values of f for streamline flow in *circular pipes* running full. (Values of f from this line cannot be used in Equation 11 for ducts of non-circular shape.) The equation of the straight

line is $f = \frac{64}{Re}$ and substituting this value of f in Equation 8 we get

$$\Delta P = \frac{64}{Re} \frac{L}{D} \frac{\rho V^2}{2} = \frac{64\eta}{VD\rho} \frac{L}{D} \frac{\rho V^2}{2} = 32 \frac{\eta LV}{D^2}$$

This is the well-known equation for streamline flow obtained by Poiseuille. The equivalent equation in the units adopted throughout this chapter (lb./sq.in.) is obtained by putting $f = 64/Re$ in Equation 10.

It is often desired to estimate the pressure drop in streamline flow when the duct is not circular. The exact equations have been worked out for a number of shapes, and as a rough guide it may be taken that values of f for various shapes will lie between those for a circular pipe and those for an annulus. The values for streamline flow in an annulus are given by the expression $f = 96/Re$

To use this equation Re is calculated using $4M$ in place of D , and the value of f obtained is used in Equation 11.

On the right-hand side of the graph are a series of lines from which f can be determined for pipes of various roughnesses in the turbulent region. The types of pipe for which these lines can be used are indicated.

Between the two regions already described lies the critical region, extending from $Re=2,000$ to $Re=3,000$. The accuracy of the graph in this region is not great, but reliable values can generally be obtained using the S-shaped lines. If, however, it is important not to under-estimate the pressure drop, or if the system has a large number of fittings such as bends and valves, the higher values given by the dotted lines should be used.

VELOCITY DISTRIBUTION

The velocity, V , used in all the equations, is the mean velocity, obtained by dividing the volume flowing through the duct or pipe by its cross-section area. The fluid is not flowing at this velocity over the whole cross section of the pipe; the velocity of the molecular layer at the pipe wall is zero, while in the centre it is flowing much faster than the average. If we consider a cross section of the pipe and plot the actual velocity of the fluid against the distance from the centre line, we get a velocity distribution curve. The shape of this curve is dependent on the Reynolds' Number; typical curves are shown in Fig. 10. When the flow is streamline the curve is a parabola; as the flow becomes

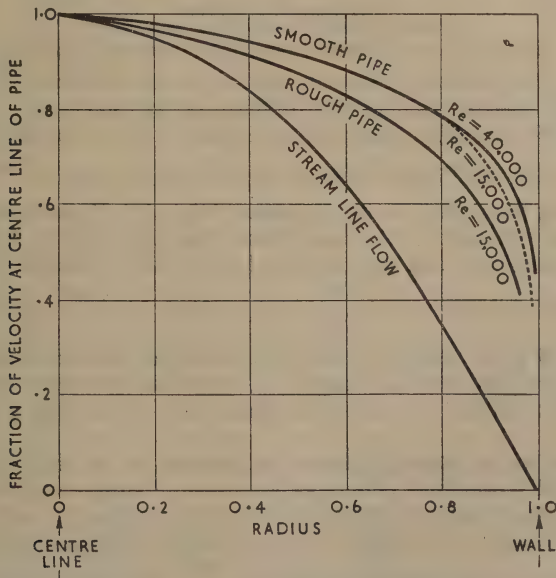


FIG. 10. Velocity distribution in pipes.

turbulent the curve flattens. An appreciation of the velocity distribution curve is essential when dealing with such things as the measurement of rates of flow by Pitot tube. The shape of the velocity curve also affects directly the kinetic energy of the fluid. For rough calculation, and in the general case, this is taken as $\frac{V^2}{2g}$. This expression is nearly correct for highly turbulent flow where, as can be seen from Fig. 10, the velocity is nearly constant over the cross section so that the mean velocity is approximately the same as that at the axis. For streamline flow, with its parabolic velocity distribution, the kinetic energy is $\frac{V_{\text{mean}}^2}{2g}$ or $\frac{1}{4} \frac{V_{\text{centre}}^2}{2g}$.

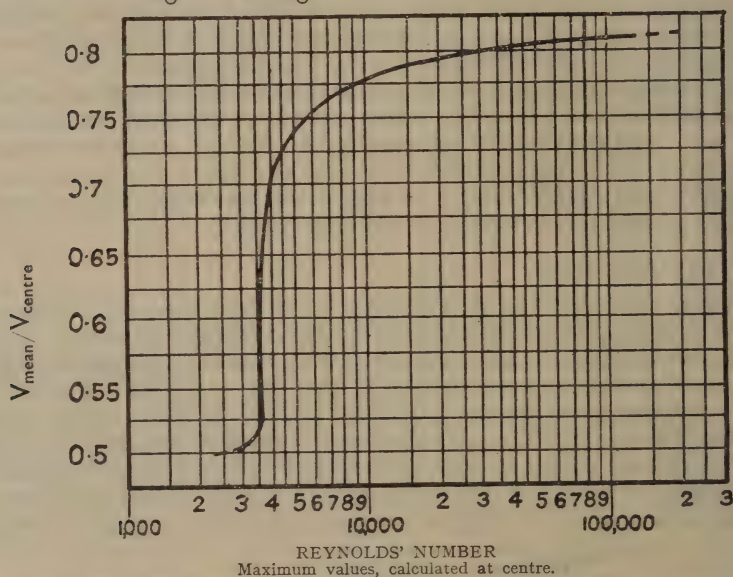


FIG. 11. Ratio of mean velocity to maximum velocity in circular pipes.

Fig. 11 shows the ratio of the mean velocity to the velocity at the centre of the tube, plotted against the Reynolds' Number at the centre. The subject of velocity distribution is of great practical importance in flow in furnaces.

ALLOWANCE FOR ENTRANCE AND EXIT LOSSES AND FITTINGS

It is customary to include in the pressure drop, ΔP , the extra pressure drop due to entrance and exit of the fluid from the pipe, and to fittings such as elbows or valves. These can be expressed either as a fraction or multiple of the velocity head pressure viz.: $\frac{wV^2}{2g}$ to be added to ΔP , or as an additional

length of straight pipe, usually given in terms of a number of pipe diameters, which must be added to the length L , used in the flow equations (e.g. Equation 10); L is measured along the centre line of the pipe with the fittings in position.

The *additional length method* is more convenient to use, but in certain cases it is fundamentally unsound. There is, however, a simple relation connecting the number of pipe diameters (N) to be added to the length, with the number of velocity heads (S) to be added to the pressure. This connection is easily derived starting with Equation 9. Adding $S \frac{wV^2}{2g}$ to the left-hand side to allow

for the effect of the fittings, and alternatively making the allowance by adding $(N \times D)$ to the length and putting this in the right-hand side, and equating the two, we get:

$$\Delta P + S \frac{wV^2}{2g} = f \left(\frac{L + ND}{D} \right) \frac{wV^2}{2g}$$

Since, from the original equation,


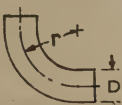
$$\Delta P = f \frac{L}{D} \frac{wV^2}{2g} \text{ then } \frac{SwV^2}{2g} = f \frac{NwV^2}{2g} \cdot \text{ Thus } N = S/f.$$

This derivation shows the method of adding the length, but it must be remembered that in the equation, in practical units, L is in feet and D in inches. The quantity ND must therefore be converted from inches to feet before adding it to L .

In Table 4 values of S are given for common fittings, together with values of N corresponding to a mean value of $f=0.025$. This table applies only to the turbulent region. In the streamline region the effects of fittings are generally negligible. The exit loss, however, is sometimes important and is equivalent to two velocity heads. In the critical region the values of the losses are open to great doubt, and it is recommended that the values in the table should be used down to $Re=2,000$.

For approximate calculations the values for N in the table may be used. In general they will be quite accurate enough, unless the calculation is being made for a short length of line with several fittings, in which case the more accurate value of N should be worked out from the values of S and f .

TABLE 4. ALLOWANCES FOR FITTINGS AND ENTRANCE AND EXIT LOSSES IN PIPES

Fitting		S	N
		Additional Velocity Heads	Additional length : pipe diameters (correct for $f=0.025$)
 Elbows of various angles	$\alpha = 90^\circ$	1.0	40
	60°	0.36	14
	45°	0.18	7
	30°	0.07	3
	15°	0.02	1
 90° bends	$r/D = 0.5$	1.0	40
	1.0	0.6	24
	2.0	0.4	16
	4.1	0.3	12
Standard tee 90°, equal areas:			
From barrel to branch		1.2	48
From branch to barrel		1.5	60
Through barrel		0.25	10
(Third leg stagnant in each case)			
Close return bend, 180° $r/D=1.0$		2.0	80
Globe valve, full open		10	400
Angle valve, 45° open		5	200
Flap non-return valve		2	80
Gate valve, full open		0.15	6
$\frac{3}{4}$ -open by area		0.8	32
$\frac{1}{2}$ -open by area		4.5	180
$\frac{1}{4}$ -open by area		28	1,120
Square entrance from a tank		0.5	20
Bell mouth entrance from a tank		0.05	2
Re-entrant (Borda) mouth piece		0.8	32
Pipe discharge into a tank		1.0	40

The allowances to be made for sudden enlargements and contractions in a pipe line are :

$$\text{sudden enlargement } S = \left(1 - \frac{a}{A}\right)^2 \quad \text{sudden contraction } S = 0.5 \left(1 - \frac{a}{A}\right)$$

where a = cross-sectional area of small section and
 A = cross-sectional area of large section.

PRESSURE DROP EQUATION FOR GASES WITH HIGH PRESSURE DROP

The calculation of the pressure drop in gas flow is complicated by the fact that the gas expands as the pressure falls and energy is available due to this expansion. In some cases the equations are most involved, but it is possible to treat the subject in a simplified manner and still retain sufficient accuracy for most purposes.

This treatment starts from Equation 7 which we can simplify by omitting the term $w(H_2 - H_1)$; i.e. it is assumed that the whole system is horizontal, or that w is so small that this term can be neglected in comparison with the others. The assumption is also made that the flow is isothermal. This is generally true in practice except in the case of flow through nozzles or orifices.

Furthermore, when dealing with gas flow it is necessary to make the calculation of pressure drop in the pipe in two parts, on each side of the compressor or throttling valve.

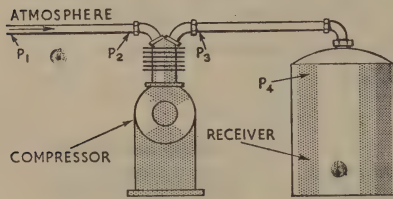


FIG. 12

Fig. 12 illustrates an example, in which air is being sucked through an inlet pipe into a compressor and discharged through a length of pipe into a pressure receiver. In order to calculate the horse-power and other characteristics of the compressor, the pressure rise across it must be determined. The pressure P_1 (atmospheric) and P_4 are fixed and the lengths and diameters of the pipes are known. On the

suction side P_2 is equal to P_1 minus the pressure drop due to friction in the line between atmosphere and compressor, and similarly on the high pressure side of the compressor P_4 is equal to P_3 minus the pressure drop in the discharge line.

The equation from which $P_1 - P_2$ can be calculated is

$$\frac{P_1^2 - P_2^2}{2P_1} = 1.295 \times 10^{-3} \frac{fLw_1V_1^2}{D} \quad \dots \dots \dots (12)$$

where L = equivalent length of line, i.e. the actual length plus an allowance of N pipe diameters for the fittings and losses.

$N = \frac{(S+E)}{f}$ where S = number of velocity heads due to fittings, but not entrance and exit losses and E is a factor to be obtained from Fig. 13. The units to be used in Equation 12 are as quoted above for Equation 10. It will be noted that there are two lines on Fig. 13; the lower one gives values of E applicable to the case where the upstream pressure is taken inside the pipe and the upper gives values when the upstream pressure is atmospheric or in a large vessel or tank. In the case considered, the lower line would be used to obtain the value of E when calculating $(P_3 - P_4)$, and the upper when calculating $(P_1 - P_2)$.

The reason for restricting S to the number of velocity heads due to the fittings and omitting the entrance and exit loss in this case is that the value of E has been chosen to include the latter.

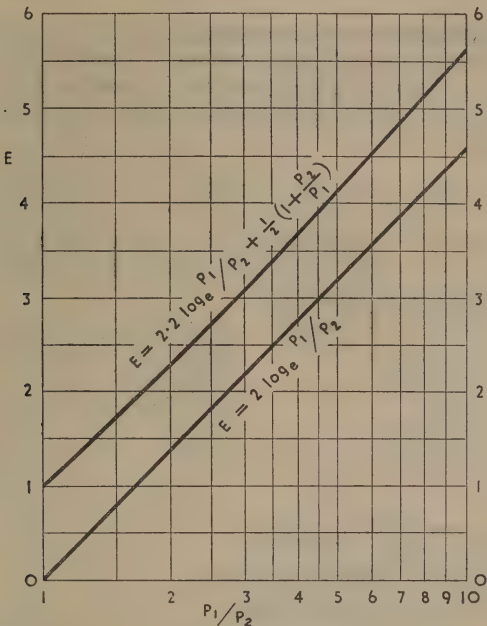


FIG. 13. Values of Entrance and Exit Factor E.

Note that, if desired, Equation 12 can also be written

$$\frac{P_1^2 - P_2^2}{2P_2} = 1.295 \times 10^{-3} \frac{fLw_2V_2^2}{D} \dots \dots \dots (13)$$

and in fact it is in this form that it would be easier to use on the high pressure side of the compressor since P_4 is known and w_4 and V_4 can therefore be calculated.

Equations 12 and 13 are related as follows: assuming the flow to be isothermal, then

$$\frac{P_1}{w_1} = \frac{P_2}{w_2} \text{ so that } P_1 = \frac{w_1P_2}{w_2}$$

also for mass continuity of flow in a pipe of uniform diameter

$$w_1V_1 = w_2V_2 \text{ so that } V_1 = \frac{w_2V_2}{w_1} \text{ and } w_1V_1^2 = \frac{w_2^2V_2^2}{w_1}$$

Substituting these values of P_1 and $w_1V_1^2$ in Equation 12 will lead directly to Equation 13.

It will be seen also that in order to use Fig. 13 and obtain a value for E it will be necessary to guess a value for P_2 . The calculation is made using the trial value of E so obtained, and the calculated value of P_2 can then be used to get a more accurate value of E from the graph. If necessary the procedure can be repeated.

FLOW FORMULAE IN TERMS OF QUANTITY FLOWING

It is convenient in many cases to use a formula in which the rate of flow is in terms of the volume of fluid flowing rather than in terms of linear velocity. Such formulae are easily derived from Equations 10 and 12, but it is most important to remember that they are applicable to circular pipes only.

The Reynolds' Number can also be calculated from expressions containing rate of volume flow instead of linear velocity. Convenient units for volume flow are *cubic feet per hour* for gases (symbol Q), and *Imperial gallons per hour* for liquids (symbol q); and the following formulae for Reynolds' Number apply in those units:

Reynolds' Number $Re = 63.3 \frac{q}{D_v} = 394.3 \frac{Q}{D_v} = 6.315 \frac{Q\rho}{D\eta}$

Note: The constants in Equations 14-18 may differ from those to be found in other text books; this is because of the difference in units used. The appropriate units are:

Pressure: P or ΔP —lb./sq.in.	Density: ρ —lb. mass/cu.ft.
do. p or Δp —in. wg.	Absolute viscosity: η —centipoises
Diameter: D —inches	Kinematic „ ν —centistokes
Length: L —feet	Gas flow rate: Q —cu.ft./hr.
Velocity: V —ft./sec.	Liquid „ „ : q —gal./hr.

Flow Formulae

(a) For liquids

$\Delta P = 8.66 \times 10^{-8} \frac{fLwq^2}{D^5}$ lb./sq.in. (14)

where q is in gallons per hour.

(b) For gases with low pressure drop

$\Delta P = 3.36 \times 10^{-6} \frac{fLwQ^2}{D^5}$ lb./sq.in. (15)

where Q is in cubic feet per hour measured at temperature and mean pressure of flow.

These two equations correspond to Equation 10.

If we substitute G_a , the specific gravity of the gas relative to air at the same temperature and pressure in place of w so that $G_a = w_{gas}/w_{air}$ and express the pressure drop in inches of water, denoted by Δp , we have:

$Q = 376 \sqrt{\frac{\Delta p \cdot D^5}{fLG_a}}$ (16)

where Q is in cu.ft./hr. measured at standard temperature and pressure (60° F. and one atmosphere). This is Lacey's Formula, and is frequently used for gases flowing at mean pressures and temperatures not far from atmospheric.

An even more convenient formula for quick rough estimates is obtained by putting an average value of 0.026 for "f" in Equation 16, giving

$Q = 2340 \sqrt{\frac{\Delta p \cdot D^5}{LG_a}}$ (17)

where Q is in cubic feet per hour measured at standard temperature and pressure. (60° F. and one atmosphere). This is Pole's Formula.

(c) For gases with high pressure drop

$\frac{P_1^2 - P_2^2}{2P_1} = 3.36 \times 10^{-6} \frac{fLw_1Q_1^2}{D^5}$ (18)

where Q_1 is in cubic feet per hour at temperature of flow and pressure P_1 .

Examples

1. A mineral oil of specific gravity 0.9 and kinematic viscosity 5 centistokes is to be pumped from a storage tank at ground level to discharge freely into an overhead tank 200 feet away and 30 feet above ground level. If the internal diameter of the pipe is 3 inches and it has to take a maximum of 2,000 gallons of oil per hour, what pressure is required at the outlet of the pump at the storage tank? (Neglect bends and assume that commercial steel pipe is used.)

Write down Equation 7 and then give numerical values to the various terms as far as is possible from the data given, as follows:

$$w(H_2 - H_1) + 144(P_2 - P_1) + 144\Delta P = 144\Delta P_p$$

w = specific weight of oil in lb./cu.ft.

= specific gravity of oil \times specific weight of water

$$= 0.9 \times 62.4 = 56 \text{ lb./cu.ft.}$$

H_2 = height of free end of pipe above ground = 30 ft.

H_1 = height of pump outlet above ground = 0 (zero)

P_2 = pressure on fluid at pipe outlet

$$= 1 \text{ atmosphere} = 14.7 \text{ lb./sq.in.abs.}$$

P_1 = pressure on fluid at pump outlet lb./sq.in.

ΔP = pressure drop due to friction in the pipe (see next section); lb./sq.in.

$\Delta P_p = 0$ (zero), since the pump is not included in the section of line considered.

Calculate ΔP , the friction loss in the pipe, including the outlet loss (but not inlet loss since the measurement is from the discharge port of the pump).

The data required are as follows:

D = diameter of line = 3 in.

L = length of line = 230 ft. plus allowance for outlet loss.

q = volume rate of flow = 2,000 gal./hr.

w = sp. wt. of oil = 56 lb./cu.ft.

ν = kinematic viscosity = 5.0 centistokes.

$$Re = 63.3 \frac{q}{D\nu} = \frac{63.3 \times 2,000}{3 \times 5} = 8,440 \quad (\text{page 210})$$

$$\epsilon/D = 0.0018/3 = 0.0006; \text{ hence use Curve C, Fig. 9.}$$

$$\therefore f = 0.034.$$

$$\text{Additional length to allow for discharge loss} = \frac{SD}{f}$$

$$S = 1.0 \quad (\text{Table 4})$$

$$\therefore \text{Additional length} = \frac{1 \times 3}{0.034} = 88 \text{ in.} = 7.3 \text{ ft.}$$

$$\therefore L = 237.3 \text{ ft.}$$

$$\Delta P = 8.66 \times 10^{-8} \frac{fLwq^2}{D^5} \quad (\text{Eqn. 14})$$

$$= \frac{8.66 \times 10^{-8} \times 0.034 \times 237.3 \times 56 \times 2,000^2}{3^5} = 0.644 \text{ lb./sq.in.}$$

Hence, applying Eqn. 7

$$56(30 - 0) + 144(14.7 - P_1) + 144 \times 0.644 = 0$$

$$\therefore P_1 = 14.7 + \frac{1,680}{144} + 0.644 = 14.7 + 12.32 \text{ lb./sq.in.abs.}$$

$$= 12.32 \text{ lb./sq.in.gauge.}$$

2. What size of gas pipe is required to transmit 600 cu.ft./hr. of town gas (sp.gr. gas relative to air = 0.45) to a point 100 feet from the gas meter, the pressure at the meter being 4 in.w.g. and that required at the point of use being $3\frac{1}{2}$ in. w.g.

The formula preferred for this case would be Lacey's (Eqn. 16). To use this we must be able to determine f , which will require a knowledge of the Reynolds' Number. The latter cannot be determined, since we do not know the diameter D . The general procedure in such a case is to assume a value for f which is

thought to be reasonable, work out a preliminary value of D , use this to obtain Re and check whether the assumed value of f is sufficiently close. If necessary the calculation may be repeated.

In the present case the first rough calculation can be made using Pole's Formula (Eqn. 17), which assumes that f has the value 0.026.

We then have:

$$\begin{aligned} Q &= 600 \text{ cu.ft./hr.} & L &= 100 \text{ ft.} \\ \Delta p &= 0.5 \text{ inches w.g.} & G_a &= 0.45 \\ Q &= 2,340 \sqrt{\frac{\Delta p D^5}{L G_a}}, \text{ or } D^5 = \frac{Q^2 L G_a}{2,340^2 \Delta p} \\ &= \frac{600^2 \times 100 \times 0.45}{2,340^2 \times 0.5} = 5.92. \\ D &= 1.43 \text{ inches.} \end{aligned}$$

In order to work out the Reynolds' Number we need a value for the viscosity of the gas, which we may take as 140×10^{-6} poises i.e. 1.4×10^{-2} centipoises. We also need ρ , the density in pounds mass per cubic foot, which is equal to the specific gravity multiplied by the density of air at S.T.P.

$$\begin{aligned} \rho &= 0.45 \times 0.076 = 0.0342 \text{ lb.mass/cu.ft.} \\ Re &= 6.315 \frac{Q \rho}{D \eta} = \frac{6.315 \times 600 \times 0.0342}{1.43 \times 1.4 \times 10^{-2}} \quad (\text{page 210}) \\ &= 6,470 \\ \therefore f &= 0.037. \quad (\text{Fig. 9, line D}) \end{aligned}$$

This is much higher than the assumed value 0.026, and a recalculation should be made. Using Lacey's Formula (Eqn. 16), we have:

$$\begin{aligned} Q &= 376 \sqrt{\frac{\Delta p D^5}{f L G_a}}, \text{ or } D^5 = \frac{Q^2 f L G_a}{376^2 \Delta p} \\ &= \frac{600^2 \times 0.037 \times 100 \times 0.45}{376^2 \times 0.5} = 8.48 \\ D &= 1.535 \text{ inches.} \end{aligned}$$

Hence, in order to ensure that the pressure at the point of use does not fall below $3\frac{1}{2}$ inches w.g. a $1\frac{3}{4}$ -in. internal diameter pipe should be used.

THE FLOW OF GASES IN FURNACES

The foregoing pages have dealt mainly with the flow of gases and liquids in pipes. Whilst the flow of gases in furnaces obeys the same fundamental laws, their interpretation is sufficiently different to warrant separate treatment.

A natural draught furnace system consists of a series of communicating chambers, open at two points to the atmosphere. Combustion gases and air are drawn through as a result of the liberation of heat by combustion at some point within the system. Furnaces depending solely on natural draught are less common than formerly, *balanced draught* being preferred. In furnaces of this type the air supply is boosted by a fan and the removal of the flue gases is assisted by another fan.

The flow of gases in existing furnaces can be studied by measuring the temperature and pressure of the gases at various points. When designing furnaces the dimensions and shape of the chambers and intercommunicating passages or flues must be fixed partly by the requirements of the process and partly by established data on the flow of gases.

The first step in the aerodynamic design of a furnace is to estimate as fully as possible the force available to bring about the required gas flow. This will be the algebraic sum of the initial pressure, the resistances of the system, and the various chimney effects, i.e. initial pressure *plus* chimney effect where hot gas rises *minus* chimney effect where hot gas descends *minus* resistances in the system.

The extent to which the main chimney “drives” the system depends on the number of openings in the system. In natural draught boilers and those natural draught furnaces having no working doors or openings for the charging of material, the chimney draught creates the motive power necessary for moving the air through the furnace and subsequent flues. In furnaces that have working doors to their heating chambers (e.g. reverberatory furnaces, open hearth steel furnaces, and puddling furnaces) the main chimney may exert little effect on the incoming system. A furnace may operate with a slight positive pressure in the furnace chamber, and following this chamber there will be a section where the pressure will be zero. From here onwards the pressure will be negative due to the effect of the “pull” exerted by the chimney.

BUOYANCY

If a closed vertical tower contains a gas lighter than air, it can be shown that the buoyancy effect of the gases sets up a difference in pressure between the top and bottom of the tower equal to the difference in weights of 1 cubic foot of air and 1 cubic foot of the lighter gas, multiplied by the height of the column, i.e.

$$\Delta P = P_1 - P_2 = \frac{H}{144} (w_a - w_g) \text{ lb./sq.in} \quad \dots \dots \dots (19)$$

where P_1 and P_2 are the gauge pressures at the top and bottom of the tower respectively, in lb./sq.in. w_a and w_g are the specific weights of the outside air and of the gas in lb./cu.ft. under the conditions prevailing, and H is the height of the tower in feet.

The value obtained by Equation 19 multiplied by 27.7 gives the pressure difference in inches w.g.

If the top of the tower is open to the atmosphere the system is in effect a chimney with the damper closed. Clearly P_1 , the pressure difference between the tower and the atmosphere, = 0, and Equation 19 becomes

$$P_2 = - \frac{H}{144} (w_a - w_g) \quad \dots \dots \dots (20)$$

P_2 being the measured static suction at the chimney base. Similarly, if the bottom were open and the top closed, $P_2=0$ and

$$P_1 = \frac{H}{144} (w_a - w_g) \quad \dots \dots \dots (21)$$

If both bottom and top were open, and the relative densities of air and gas were maintained—this being the condition met in practice—there would be a flow of gas up the chimney resulting from exactly the same cause, but part of the static pressure difference $P_1 - P_2$ would be converted into velocity head and part would be lost in friction. (See page 226.)

EFFECT OF BENDS AND OBSTRUCTIONS

The effect of these on pressure drop in a pipeline has already been discussed (see Table 4). In an industrial furnace there are inevitably a number of bends in the flues, and there are obstructions in the form of regulating valves, dust

catchers, and recuperators or regenerators. In the large flues and ducts encountered in large furnaces, which carry hot gases often at a different temperature from that of the flue surface, a more complex system of flow occurs. This arises mainly from the separation of hot and cold layers of gas in the furnaces, the effect of burners, and the location of flue offtakes. For this reason the calculation of pressure drop in furnaces cannot be so precise as that in pipe systems but it is still essential in order to ensure proper design and satisfactory service. This effect is discussed below, in greater detail.

PRESSURE DROP IN FURNACES

The resistance to gas flow through the system must be calculated to ensure that the necessary quantities of gas and air will enter the furnace with the pressure available and to calculate the draught necessary to exhaust the waste gases and infiltrated air. Most of the pressure drop is caused by the numerous bends and changes of section, and is due in only a minor degree to wall friction. In addition, pressure changes are caused by the variations in vertical level through the furnace system, and the gas temperature is constantly changing. Therefore it is preferable to calculate the pressure drop in sections, and in terms of velocity head, rather than of equivalent length. Since the pressure changes involved are always very small in relation to absolute pressure one may neglect the compressibility of the gases.

The total static pressure change ΔP through a furnace system is divisible into three components (a) that due to the eddying at bends, and changes of section, (b) that due to wall friction and (c) that due to changes in vertical level of hot gases (buoyancy changes). (a) and (b) are proportional to the square of the velocity and are expressed in terms of the pressure equivalent of the kinetic energy ΔP_v ; in this discussion they are denoted collectively by ΔP_v ; (c) is independent of the velocity and is denoted by ΔP_b .

CALCULATION OF ΔP_v

The relation between ΔP_v and ΔP_v is:

$$\Delta P_v = (S' + f') \Delta P_v \quad (22)$$

where S' is a factor allowing for losses due to eddying at bends and changes of section (Fig. 14); f' is the friction factor analogous to f in Equation 10 (see Eq'n 26).

ΔP_v is the pressure equivalent of the kinetic energy $\left(\frac{wV^2}{2g}\right)$ thus we have:

$$\Delta P_v = \frac{wV^2}{2g} \text{ lb./sq.ft.} \quad (23)$$

where w and V are measured at the temperature of operation.

It is generally more convenient to express pressure in terms of inches w.g. velocity at 32°F. and 29.92 in. Hg. (N.T.P.), V_o , and specific gravity G_a , where G_a is the density of the gas relative to air. Air, which has a density of 0.08071 lb./normal cu.ft.*, is taken as 1.

Equation 23 then becomes

$$\Delta P_v = \frac{0.08071 G_a V_o^2}{2g} \left(\frac{273+t}{273}\right) \text{ lb./sq.ft.} \quad (24)$$

*This value for the density of air applies under N.T.P. conditions and Equation 24 takes care of temperature in the temperature term. Most industrial plants are situated within a few hundred feet of sea level so that variations in atmospheric pressure can be neglected. In certain special locations, such as the highlands of South Africa, where the plant may be several thousand feet above sea level, Equations 24 and 25 may need to be modified to allow for the reduced density of air at these high altitudes, i.e. the value will be smaller.

and, since 12" w.g. equals 62.43 lb./sq.ft.

$$\Delta P_e = \frac{12}{62.43} \frac{0.08071}{2 \times 32.17 \times 273} G_a V_o^2 (273 + t)$$
$$= 8.81 \times 10^{-7} G_a V_o^2 (273 + t) \text{ in. w.g.} \quad (25)$$

This gives the value of ΔP_e for use in Equation 22. Values of S' for varying configurations found in furnaces are given below. It is advisable to use S' , and not the factor S given in Table 4, because it is found in practice that in the relatively large rough-walled flues which exist in furnaces, bend and change-of-section losses expressed in terms of velocity head seem to be appreciably larger than those encountered in pipelines (though in furnaces the velocity heads themselves are generally very much lower).

Values of S' for Various Bends, etc. in Furnace Flues and Ducts

In some cases data are available showing values for S' for ducts of rectangular and circular sections. These are indicated by \square or \odot after the S' figure quoted. (See also Fig. 14.)

- (a) Right angle bend — $S' = 1.5 \square, 1.2 \odot$.
- (b) Right angle bend made from T-piece by closing one end — $S' = 2.0 \square$.
- (c) Bend of angle α ($\alpha < 90^\circ$) — $S' = 1.5 (1 - \cos \alpha) \square, 1.2 (1 - \cos \alpha) \odot$,
- (d) Curved bend — S' varies with $\frac{R}{D}$ as follows, where R = axial radius of curvature, and D = internal diameter of duct:

$\frac{R}{D} =$	0.5	0.75	1.0	2.0
$S' \square$	1	0.3	0.17	0.04
$S' \odot$	0.9	0.35	0.25	0.07

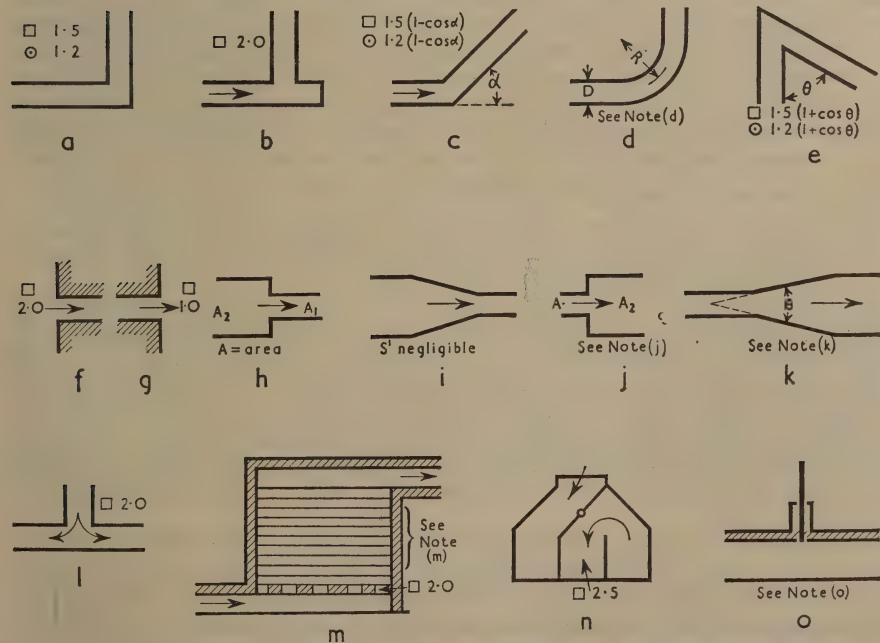


FIG. 14. Bends, changes of section etc., common in furnace systems.
Values of S' for square and round sections respectively are shown thus: \square, \odot .

- (e) Sharp bend, inner corner not rounded off—

$$S' = 1.5 (1 + \cos\theta), \square, 1.2 (1 + \cos\theta), \odot,$$

- (f) Entry to passage from large chamber or from atmosphere— $S' = 2.0\square$

- (g) Exit from passage to large chamber or to atmosphere— $S' = 1.0\square$

- (h) Sharp-edged contraction— S' depends on the ratio of the areas. Standard curves showing S' plotted against this ratio are given in text-books but in practice it is found that the S' values so obtained are too low and the value used should be about three times that given by the curve. The recommended values of $S'\square$ are as follows:

Area ratio (A_1/A_2):	0.1	0.2	0.4	0.6	0.8	1.0
S' :	1.08	1.02	0.81	0.5	0.16	0

- (i) Gradual narrowing — S' very small and may be taken as zero.

- (j) Sharp-edged enlargement— $S' = \left(\frac{A_2 - A_1}{A_2}\right)^2$

where A_1 is upstream and A_2 is downstream area.

- (k) Gradual enlargement— $S' = k\left(\frac{A_2 - A_1}{A_2}\right)^2$

k has the following values¹ for a gradual enlargement in a pipe having a total angle of θ° :

θ :	5-8	14	20	30	45	60	90-180 deg.
k :	0.14	0.25	0.45	0.7	0.95	1.1	1.0

- (l) Separating flow — S' varies according to configuration, and its estimation is complicated. In the simple cases found in furnaces it is probably sufficient to regard S' as equal to 2.0 whenever a gas stream is divided into two or more branches.

- (m) Checkers—For entry to checkers $S' = 2.0$. For the checker courses themselves the S' value of 0.3* per course of bricks for unstaggered patterns is suggested by Etherington², and this seems to work well in practice. However, it must be applied to the velocity in the checkers and in calculating this it should be borne in mind that the theoretical free area of cross-section is seldom effective. The effective free area seems to be $\frac{1}{2}$ to $\frac{2}{3}$ of the theoretical free area according to the layout.

- (n) Reversal of flow, e.g. in a reversing valve— S' is approximately 2.5.

- (o) Dampers—If damper is fully open, S' may be taken as 0; if partly closed it should be treated as a contraction followed by an enlargement, the values from (h) and (j) being added.

It is not permissible to compute the loss of a complicated system by the simple addition of the S' components unless the components are some distance apart. Unfortunately little data are available on the combined effect of bends and changes of section. In some cases the combined S' value for two features in close proximity may be greater than the sum of the separate values and, in other cases, less. Until further data become available all that can be done is to calculate a complicated system on an additive basis on the assumption that cases where the error is on one side are balanced by cases where the converse is true.

The value of f' in Equation 22 now requires consideration. It has already been shown (page 204) that this depends on flow conditions, but for most furnace work involving rough walled flues several square feet in cross-section, a constant value for the friction itself may be taken making f' depend on

* The f' value for checkers is included in this.

length (L) and mean hydraulic diameter (M) only. The friction equation corresponding to Equation 11 is

$$f' = f \frac{L}{4M} = 0.0125 \frac{L}{M} \quad \dots \quad (26)$$

CALCULATION OF ΔP_b (pressure difference due to buoyancy changes)

$$\Delta P_b = \frac{H}{144} (w_a - w_g) \text{ lb./sq.in. (Equation 19)}$$

$$w_a = \frac{0.08071 (273)}{(273 + t_a)} \text{ and } w_g = \frac{0.08071 G_a (273)}{(273 + t_g)}$$

where t_a and t_g are the air and gas temperatures, ($^{\circ}\text{C.}$)

Since $12'' \text{ w.g.} = 62.43 \text{ lb./sq.ft.}$,

$$\begin{aligned} \Delta P_b &= \frac{H \times 0.08071 \times 273 \times 12 \times 144}{144 \times 62.43} \left(\frac{1}{273 + t_a} - \frac{G_a}{273 + t_g} \right) \\ &= 4.236H \left(\frac{1}{273 + t_a} - \frac{G_a}{273 + t_g} \right) \quad \dots \quad (27)^* \end{aligned}$$

For most furnace calculations it is permissible to assume an air temperature of 15°C. and a value of $G_a = 1$ for furnace waste gases; Equation 27 then becomes

$$\Delta P_b = 0.0147H \left(1 - \frac{288}{273 + t} \right) \quad \dots \quad (28)$$

EXAMPLES OF CALCULATION OF FURNACE GAS FLOW

A regenerative slab heating furnace is to be constructed to the lines and dimensions given in Figs. 15, 16. The producer gas flow to the furnace is 137,000 cu.ft./hr. (measured at N.T.P.). The gas enters at 500°C. and is pre-heated to 800°C. The air required is 140,000 cu.ft. per hour† (or 38.9 cu.ft./sec.), measured at N.T.P., and enters from the atmosphere, being pre-heated in the checkers to 900°C. It is necessary to know:

- (a) the gas pressure needed at the reversing valve,
- (b) whether an air fan is necessary,
- (c) the draught needed in the stack flue.

The pressure balances are most conveniently calculated in tabular form. Table 5 is for ingoing gas and Table 6 for ingoing air. The furnace is divided into sections listed in Column 1. Column 2 shows the average temperature likely to be encountered in each section. Columns 3, 4 and 5 show the length, mean hydraulic diameter, and cross-sectional area of the passages concerned. Column 6 gives the calculated N.T.P. velocity in that particular section. Column 7 shows the velocity head ΔP_v calculated from Equation 25. Columns 8–10 give the S' and f' values; reasons for the selection of these values are given in the Notes to Tables. Finally, the resulting value of ΔP_v is tabulated in Column 11.

ΔP_b is separately tabulated below the ΔP_v table.

*This equation will need modification for plants at high altitudes (see footnote to page 214).

† This quantity of air is less than the theoretical for complete combustion, but is the required inflow so that after allowing for infiltration, the atmosphere in the working chamber is not excessively oxidising.

*Figures
in circles
indicate pressures
to be expected
with ingoing
gas & air
(in. W.G.)*

ROUGH SCALE 0 5 10 FT.

SECTION ACROSS WORKING CHAMBER

AIR PORT 13.5 \square'

2 GAS PORTS
= 1.8 \square'

2 AIR UPTAKES
= 4.5 \square'

2 GAS UPTAKES
= 3.5 \square'

AIR PORT

GAS PORTS

+0.02
inside
port

+0.38
inside
port

+1.06

+0.20

GAS CHECKER
25 COURSES

AIR CHECKER
25 COURSES

ELEVATION

7.5 \square'

11 \square'

TOTAL AREA OF
3 FLUES

*At entry
to these
flues
Gas +1.01
Air +.42*

FIG. 15. Layout of regenerative heating furnace, to illustrate the method of calculating the pressure balance.

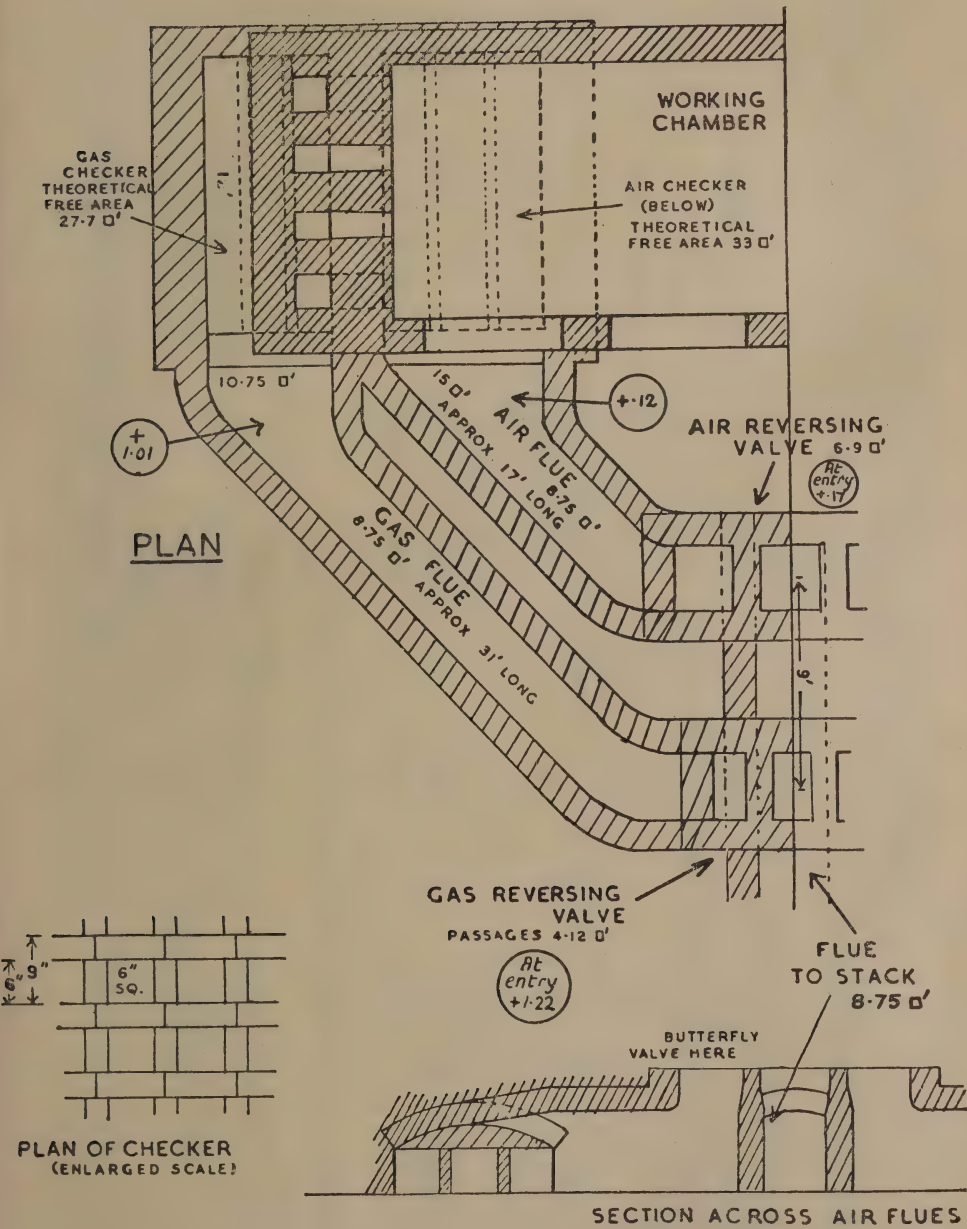


FIG. 16. Layout of regenerative heating furnace (cont.).

TABLE 5. PRESSURE BALANCE FOR INGOING GAS

Specific gravity of gas = 0.87 (air = 1)

Calculation of ΔP_v (see notes following Table 7.)

1	2	3	4	5	6	7	8	9	10	11
Part of furnace	Average Temp. (° C.)	Length L (ft.)	Mean Hydraulic Diameter M (ft.)	Area A (sq. ft.)	V_o ft./sec. at N.T.P.	ΔP_o (in. w.g.)	S'	f' from Eqn. 26	$S' + f'$	ΔP_v from Eqn. 22 (in. w.g.)
Reversing valve	500	—	—	4.12	9.22	0.0504	4.2 ⁽⁶⁾	—	4.2	0.2117
Flue	500	31	0.76	8.75 to 10.75	4.34 ⁽⁴⁾	0.0111	0.6 ⁽⁷⁾	0.51	1.11	0.0123
Under checkers (3 flues) ..	500	—	—	7.5 ⁽²⁾	5.07 ⁽⁵⁾	0.0152	2.3 ⁽⁸⁾	—	2.3	0.0350
Checkers (25 courses) ..	650 (mean)	—	—	18.5 ⁽³⁾	2.05	0.0030	10.5 ⁽⁹⁾	See Note 9	10.5	0.0315
Uptakes (two) Lower mouths Main portion	800	8	0.33 ⁽¹⁾	5.6 3.5 ⁽²⁾	6.79 10.9	0.0379 0.0976	2.0 ⁽¹⁰⁾ —	— 0.30 ⁽¹⁰⁾	2.0 0.30	0.0758 0.0293
Ports (two)	800	3	0.25 ⁽¹⁾	1.8 ⁽²⁾	21.14	0.3671	2.7 ⁽¹¹⁾	0.16	2.86	1.0499

Notes following Table 7, refer to the figures given within brackets in the tables.

Calculation of ΔP_b										
Buoyancy in checkers .. ..	..	..	..	..	12 ft. @ 650° = 0.1286 in.				..	1.4455
Net buoyancy in uptakes and ports ..	..	..	..	..	8 ft. @ 800° = 0.0900 in.				..	0.2086
Total buoyancy assisting flow ..	..	..	..	..	0.2186 in.				..	
Less furnace pressure (opposing flow), say ..	..	..	..	..	0.0100 in.				..	
					0.2086 in.					

NET PRESSURE REQUIRED AT REVERSING VALVE

1.2369 in. w.g.

TABLE 7. DRAUGHT BALANCE FOR OUTGOING WASTE GAS

Volume of waste gas (including infiltrated air) is taken as 293,000 cubic feet per hour (measured at N.T.P.), 30 per cent. of which is assumed to pass through the gas regenerative system and 70 per cent. through the air system. Density of waste gases may be taken as the same as air.

Calculation of ΔP_v (see notes on page 223.)													
1		2											
Part of furnace		Gas System							Air System				
		3 V_o ft./sec. at N.T.P.	4 ΔP_b (in. w.g.)	5 S'	6 f'	7 $S'+f'$	8 ΔP_o (in. w.g.)	9 V_o ft./sec. at N.T.P.	10 ΔP_e (in. w.g.)	11 S'	12 f'	13 $S'+f'$	14 ΔP_v (in. w.g.)
Ports	1,400	13.6	0.2710	3.96 ⁽¹⁶⁾	0.16	4.12	1.1165	4.22	0.0263	4.0 ⁽²¹⁾	0.04	4.04	0.1063
Uptakes	1,400	6.97	0.0716	—	0.3 ⁽¹⁷⁾	0.3	0.0215	12.7	0.2373	4.3 ⁽²²⁾	0.35	4.67	1.1082
(Lower mouths of gas uptakes treated separately)		4.37	0.0281	1.0 ⁽¹⁷⁾	—	1.0	0.0281						
Checkers	1,000 (mean)	1.32	0.0019	10.5 ⁽⁹⁾	see note 9	10.5	0.0120	2.59	0.0075	10.5 ⁽⁹⁾	see note 9	10.5	0.0788
Under checkers ..	600	3.25	0.0081	0.1 ⁽¹⁸⁾	—	0.1	0.0008	5.18	0.0206	0.1 ⁽¹⁸⁾	—	0.1	0.0021
Flues	600	2.79	0.0060	0.6 ⁽¹⁹⁾	0.51	1.11	0.0067	6.52	0.0326	0.6 ⁽¹⁹⁾	0.22	0.82	0.0267
Reversing valves ..	600	5.92	0.0270	6.51 ⁽²⁰⁾	—	6.51	0.1758	8.25	0.0524	5.74 ⁽²³⁾	—	5.74	0.3008
Stack flue between air and gas reversing valves	600	—	—	—	—	—	—	6.52	0.0326	—	0.15 ⁽²⁴⁾	0.15	0.0049

Notes given below refer to the figures given within brackets in the tables.

TOTAL ΔP_v (opposing flow) for gas system 1.3614 for air system 1.6278

Calculation of ΔP_b Gas System Air System

Buoyancy in uptakes, etc. 8 ft. @ 1,400° = 0.0974 in. = 0.1279 in.

Buoyancy in checkers 12 ft. @ 1,000° = 0.1368 in. = 0.1368 in.

Total buoyancy opposing flow 0.2342 in. 0.2647 in.

Less furnace pressure assisting flow, say 0.0100 in. 0.0100 in.

TOTAL ΔP_b 0.2242 in. 0.2547 in.

Substituting these values of ΔP_v and ΔP_b in Equation 29 shows that the true partition of waste gases will be about 32 per cent. through the gas checker, and give 1.78" as the draught required.

NOTES ON TABLES 5-7

- (1) Mean hydraulic diameter of each passage.
- (2) Total area of passages.
- (3) Two-thirds of the theoretical free area. In a less favourable layout such as an open hearth furnace provided with slag-pockets, half the theoretical free area should be used.
- (4) These velocities are calculated from the smaller area in the previous column, this being the area over most of the length of this particular section.
- (5) Velocity at entry. This gradually decreases along the passage as the gas enters the checkers.
- (6) Entry from gas box $S'=2.0$; 90° bend at bottom—1.5; enlargement to flue (area ratio 0.48).—0.7. Total 4.2.
- (7) Two slightly rounded bends at 0.3 each (instead of 0.44) $S'=0.6$.
- (8) For contraction from 10.75 to 7.5 sq.ft. $S'=0.3$. Division into 3 passages $S'=2.0$. Total 2.3.
- (9) Entry to checker $S'=2.0$; 25 courses at 0.3—7.5; emergence from checker to collecting space at top—1.0. Total 10.5. The f' value for checkers is included in the assumed 0.3 per course of brick.
- (10) The S' value of 2.0 for the entry to the uptakes is applied to the velocity in the enlarged entry section. The gradual narrowing afterwards does not occasion any further S' value, but the f' value is applied to the velocity in the 3.5 sq.ft. section, which covers most of the length.
- (11) Somewhat rounded bend into port S' (assumed)=1.5. Assume 0.2 for the contraction on entering the port, which is made rather gradual by the slight rounding of the bend. Loss of velocity head on entering the furnace 1.0. Total 2.7.
- (12) Entry from open air $S'=2.0$. Two 45° bends in butterfly valve— $2 \times 1.5 (1 - \cos 45^\circ) = 0.88$; bend into flue at bottom—1.5. Enlargement into flue—0.05. Total 4.43.
- (13) Contraction from 15 sq.ft. to 11 sq.ft. $S'=0.26$. Division into three passages $S'=2.0$, say. Total 2.26.
- (14) Entry to uptakes—2.0. One 45° bend—0.44. Enlargement into port—0.45. Total 2.89.
- (15) Sharp bend into port—2.0. Exit to furnace—1.0. Total 3.0.
- (16) Entry from furnace—2.0. Bend into uptake—1.5. Enlargement to uptake—0.46. Total 3.96.
- (17) It is assumed that for the gradual widening of the gas uptake at the bottom the S' value is negligible. The S' value of 1.0 for the exit into the space above the checkers is therefore applied to the velocity leaving the widened portion of the uptake.
- (18) Enlargement on leaving passages below checkers $S'=0.1$. Although there is an apparent contraction from the free area of the checker to the passages below, the velocity in these passages is gradually built up as the gases enter from the checkers over a considerable length. This is similar to the effect of a gradual contraction for which S' is negligible.
- (19) The contraction in the outgoing flues is gradual, causing a negligible S' loss. Two rounded 45° bends give an S' value of 0.6 as in Note (7).
- (20) Contraction 8.75 sq.ft. to 4.12 sq.ft.—0.73. Two 90° bends entering and leaving valve at 1.5 each—3.0. Valve itself—2.5. Enlargement to 8.75 sq.ft. of stack flue—0.28. Total 6.51. The build-up of S' for the waste gases in the gas reversing valve is, of course, different from that shown in Note (6) for the incoming gas because of the internal geometry of the "Forster" valve.
- (21) Entry—2.0; sharp bend into uptake—2.0. Total 4.0.
- (22) Division into two passages—2.0. Contraction—0.88. Exit at bottom of uptake—1.0. 45° bend—0.44. Total 4.32.
- (23) Contraction from 8.75 sq.ft. to 6.9 sq.ft.—0.17. Two 90° bends—3.0. Valve itself—2.5. Enlargement to stack flue of area 8.75 sq.ft.—0.07. Total 5.74.
- (24) Length of stack flue between reversing valves 9 ft. approx. Mean hydraulic dia. 0.76 ft. Hence $f'=0.15$ from Equation 26.

It will be noted that in several parts of the furnace, values of L , M and f' are not tabulated. This is because L is so small that f' is negligible and knowledge of these quantities is not required.

Table 7 is the draught balance for the waste gases. Since the dimensions L , M and A are already listed in Tables 5 and 6, these columns are not repeated.

In calculating the resistance for the outgoing gases a slight complication is introduced by division of the waste gases between the gas and air checkers. This is surmounted by assuming an arbitrary partition, say 30 per cent., through the gas checker and 70 per cent. through the air checker. The resist-

ances will then usually work out to a different value for each path. It is known that the total pressure change through each path must be the same and that ΔP_v depends on the square of the gas velocity while the buoyancy effect, ΔP_b , does not change with velocity. Hence, if x is the true partition, and ΔP_v the eddy losses calculated on a basis of 30 per cent. through the gas checkers, we have

$$\left(\frac{x}{0.3}\right)^2 \Delta P_v + \Delta P_b = \left(\frac{1-x}{0.7}\right)^2 \Delta P_v + \Delta P_b \quad . \quad . \quad . \quad (29)$$

(for gas system) (for air system)

In the present example Table 7 shows that ΔP_v for the waste gases passing through the gas system is 1.3614 in.w.g. and for those passing through the air system is 1.6278 in.w.g., assuming a 30 per cent. partition through the gas system; ΔP_b is 0.2242 in. and 0.2547 in. for the gas and air systems respectively. Substituting these values in Equation 29,

$$\left(\frac{x}{0.3}\right)^2 \times 1.3614 + 0.2242 = \left(\frac{1-x}{0.7}\right)^2 \times 1.6278 + 0.2547,$$

$$\therefore x = 0.321.$$

Hence under the specified conditions about 32.1 per cent. of the outgoing waste gases will pass through the gas regenerative system and the draught required in the stack flue is found by putting $x = 0.321$ in either side of the above equation.

Calculation of the pressure balances shows that:

- (1) The gas pressure required before the reversing valve is 1.24 in. w.g. (from Table 5).
- (2) An air fan to give 0.15 in. w.g. at the entrance to the air reversing valve will be necessary (from Table 6).
- (3) A stack giving 1.8 in. w.g. draught in the stack flue is required.

These tables show that much of the resistance is caused by the uptakes which could be enlarged with advantage. For instance, if it is desired to avoid the installation of an air fan, and to run the furnace on "natural" air ΔP_b for the ingoing air must exceed ΔP_v , therefore the cross-sectional area of the uptakes should be increased until ΔP_v is reduced by the required amount.

It will be understood that whilst the above example is intended to provide an illustration of how to deal with most of the bends, contractions and divisions usually met with in furnaces, no general rules, except in the simplest cases, can be laid down. The choice of S' for very complex bends and changes of section, often occurring together, it is largely a matter of intelligent estimation until more experimental data become available. Whilst the total result must be regarded as only approximate, particularly as the internal surfaces of most high-temperature furnaces change as the furnace gets older, calculation of the pressure balances by the above method is an invaluable guide to show the existence of bottlenecks and where alterations are required. Where quantities such as S' are uncertain, it is preferable to err on the high side as it is much easier to control flow in a generously designed furnace by dampers or chokes than to enlarge passages after they have been built too small.

THE FURNACE CHAMBER

In designing a furnace chamber special attention must be given to (a) proper mixing of the arriving fuel and air so as to give proper combustion, (b) attainment of correct flame conditions so that the maximum amount of heat is transferred to the stock or furnace charge, and (c) control of the hot gases so as to cause the minimum damage to the refractories.

In addition, there are many problems peculiar to particular processes; for

instance, in certain heating furnaces a special atmosphere is required, necessitating either the addition of inert gases, or interfering with thermally correct combustion conditions so as to give the required atmosphere. In other furnaces a chemical reaction is performed (for example, in glass melting or metallurgical refining furnaces) and the working chamber has to be designed with this in mind. These special cases cannot be considered in detail here, and all that can be discussed are general principles, each industry having to adapt them to its own special conditions.

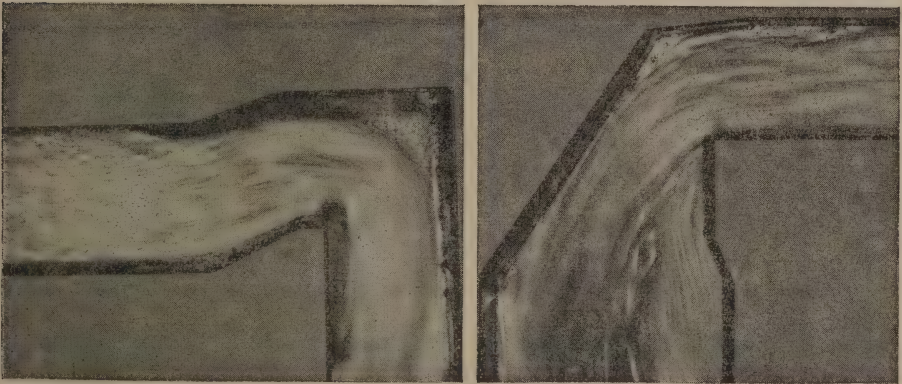
In the low and medium-temperature furnaces (operating below about $1,000^{\circ}\text{C.}$) fuel and air without pre-heat are used and a fairly wide choice of burners is available. However, for high temperature furnaces operating much above $1,000^{\circ}\text{C.}$ pre-heat of at least the air is desirable, and to reach the higher temperatures (e.g. for steel or glass melting) with a lean fuel such as producer gas pre-heat of both gas and air is essential. With pre-heated gas and air the use of special burners giving some degree of pre-mixing is not practicable since intense combustion in the burner would take place and destroy it.

Gas burners for high-temperature furnaces thus produce pure diffusion flames in which the air for combustion has to be entrained with the outer surface of the gas jet leaving the burner. The theory of such mixing has been well developed by many experimenters. In brief it may be said that rapid mixing and good combustion are favoured by

- (a) high velocity of gas and air at the burner,
- (b) a large difference of velocity between gas and air,
- (c) a large angle of impingement of the gas and air jets,
- (d) the use of multiple burners.

The actual flow pattern of the gases in the furnace chamber can have a considerable effect on heat transfer and refractory wear. As yet, the flow pattern cannot be worked out theoretically but must be studied empirically by some form of visualisation technique. Some of the earliest of such experiments were those of Groume Grjmailo. Recently the work of Chesters, Thring and their co-workers has carried this much further, and in this latter model work special care was taken to ensure correct similarity conditions between the models used for the experiments and actual practice. Other furnace model work using actual combustion has been carried out by the British Iron and Steel Research Association.³

Figs. 17 A and B, reproduced from a paper by Chesters⁴, illustrate that the



A B
FIG. 17. Flow pattern at bends in pipes.

flow pattern technique can be used to reveal conditions likely to lead to refractory wear. A study of Fig. 17A would lead one to expect excessive wear on the end wall due to the sudden change in direction of the gas stream, whilst the more tangential flow observed in Fig. 17B suggests a way in which wear could be reduced. These indications from the model work are supported by experience on actual furnaces, where end-wall life in the target area has been as much as doubled by the change to a sloping end.

The theories governing the sound design of the working chambers of high temperature furnaces are still in the early stages of development and much more experimental work is necessary before general rules of construction can be drawn up.

PRESSURE DROP IN CHIMNEYS

Loss of draught due to high gas velocities can now be considered. Chimney area is calculated on the principle that a given gas velocity, calculated at the mean chimney temperature, is permissible. In Chapter 8 this velocity is stated to be 15 ft./sec. With gas velocities higher than this, draught is reduced because of the increase in pressure energy and the loss due to friction. This loss of draught may be calculated from Equations 22-26.

For chimneys: $\Delta P_v = (1 + f') \Delta P_o$

$$= \left(1 + \frac{0.05H}{D}\right) 4.9 \times 10^{-7} G_a V_o^2 (460 + t) \text{ in. w.g.}$$

where H and D are the height and the diameter of the chimney, in feet, t is the mean temperature of the gases in the chimney in deg. F., and G_a may be taken, for flue gas, as 1.

As an example a chimney 100 ft. high and 6 ft. diameter, designed to pass 425 cu.ft. of gas per sec. at a mean temperature of 400° F. may be considered. This corresponds to a value, for V, of 15 ft./sec. or, for V_o of 8.6 ft./sec.

From the above,

$$\Delta P_v = \left(1 + \frac{0.05 \times 100}{6}\right) 4.9 \times 10^{-7} \times 1 \times (8.6)^2 \times 860$$

$$= 0.057, \text{ (say) } 0.06 \text{ in w.g.}$$

It is further assumed that in these conditions coal is being burnt with 50 per cent. of excess air. The effect of excess air on chimney draught, if the flue gas temperature can be assumed to be unaffected by the extra air, is as shown below.

<i>Excess air</i>	<i>CO₂ in flue gases: per cent.</i>	<i>Total gas flow cu.ft./sec. at 400° F.</i>	<i>V_o ft./sec. (at 32° F.)</i>	<i>Loss of pressure in chimney; in.w.g.</i>
50	12.5	425	8.6	0.06
100	9.4	570	11.5	0.10
200	6.2	850	17.2	0.23
300	4.7	1,130	22.9	0.40

Excess air overloads the chimney in the same manner as does connecting too many boilers to the chimney.

Where there is an inleakage of cold air after the furnace, the temperature of the gases may fall and cause a reduction in draught. Although the loss of pressure in the chimney may be less than shown in the table, owing to the lower mean chimney temperature and to the resulting reduced gas volume, the loss of draught caused by the fall in temperature is usually the major item.

With 50 per cent. of excess air and a mean chimney temperature of 400°F . it is found, from Fig. 2, Chapter 8, that the static draught (with an air temperature of 32°F .) is 0.85 in. w.g. However, as the gases are in motion the deduction in respect of the increase in pressure energy and the loss due to friction must be made. This is shown in the above table to be 0.06 in. w.g. for these conditions. Thus the actual draught is 0.85 *minus* 0.06, i.e. 0.79 in. w.g. If the excess air increases to 200 per cent. and the mean chimney temperature remains at 400°F . the resultant draught will be 0.85-0.23, i.e. 0.62 in. w.g. Should the mean temperature fall to 250°F . due to the inleakage of air (and it could fall even lower) the draught will be 0.45-0.19, i.e. 0.26 in. w.g. Cold air infiltration after or near the end of a boiler is thus even more detrimental to draught than is the admission of too much excess air through the furnace.

STRATIFICATION

When it is desired to measure the average temperature or obtain a representative sample for analysis from a flowing fluid, it is important to take into account the possibility of stratification. The term "stratification" is used here in the sense that the composition or temperature—or both—of the flowing fluid is not uniform over the whole cross-section.

Stratification may be initiated when fluids of different composition or temperature are brought together, familiar examples being :

1. Furnace gases of varying composition and temperature from uneven fuel beds.
2. Air infiltration.

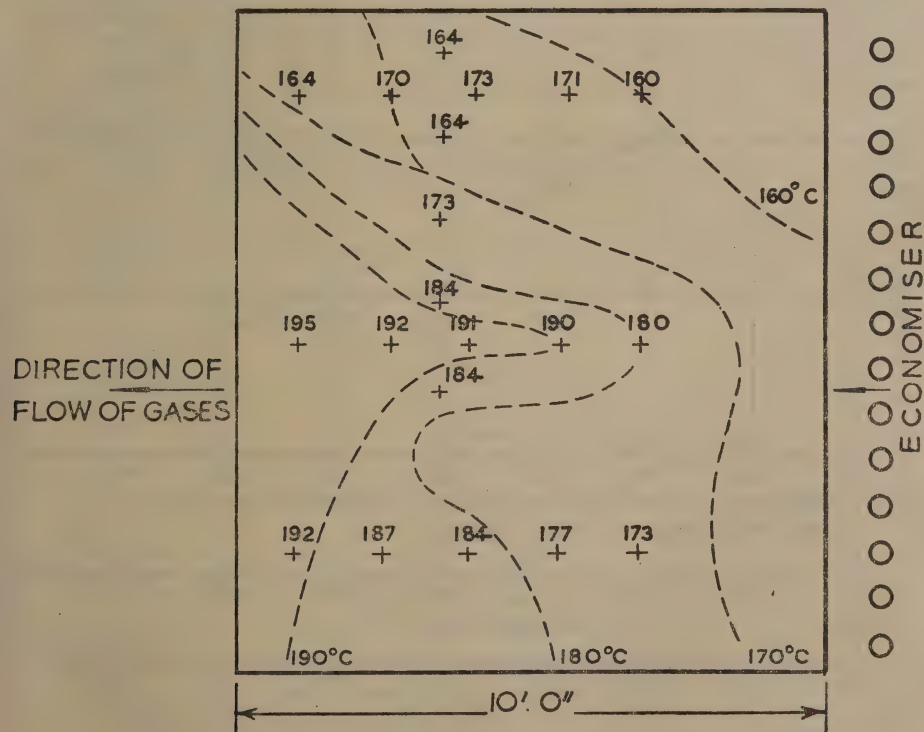


FIG. 18. Stratification of gases at an economiser outlet.

3. Flues collecting waste gases from different sources—such as from air and gas regenerators or recuperators.
4. Local cooling giving rise to stray currents.
5. Jet effects introduced by high velocity streams entering those at lower velocity.

The persistence of stratification is very variable and is influenced by the dimensions of the pipe, flue, etc., and by degree of turbulence as characterized by the Reynolds' Number as well as by factors such as the "mixing" effect of any confluent streams, diffusion, density difference and, in the case of temperature stratification, rate of heat transfer.

For pipes and flues up to about 12 inches in diameter, it is generally presumed that stratification will quickly disappear if the flow is turbulent. In

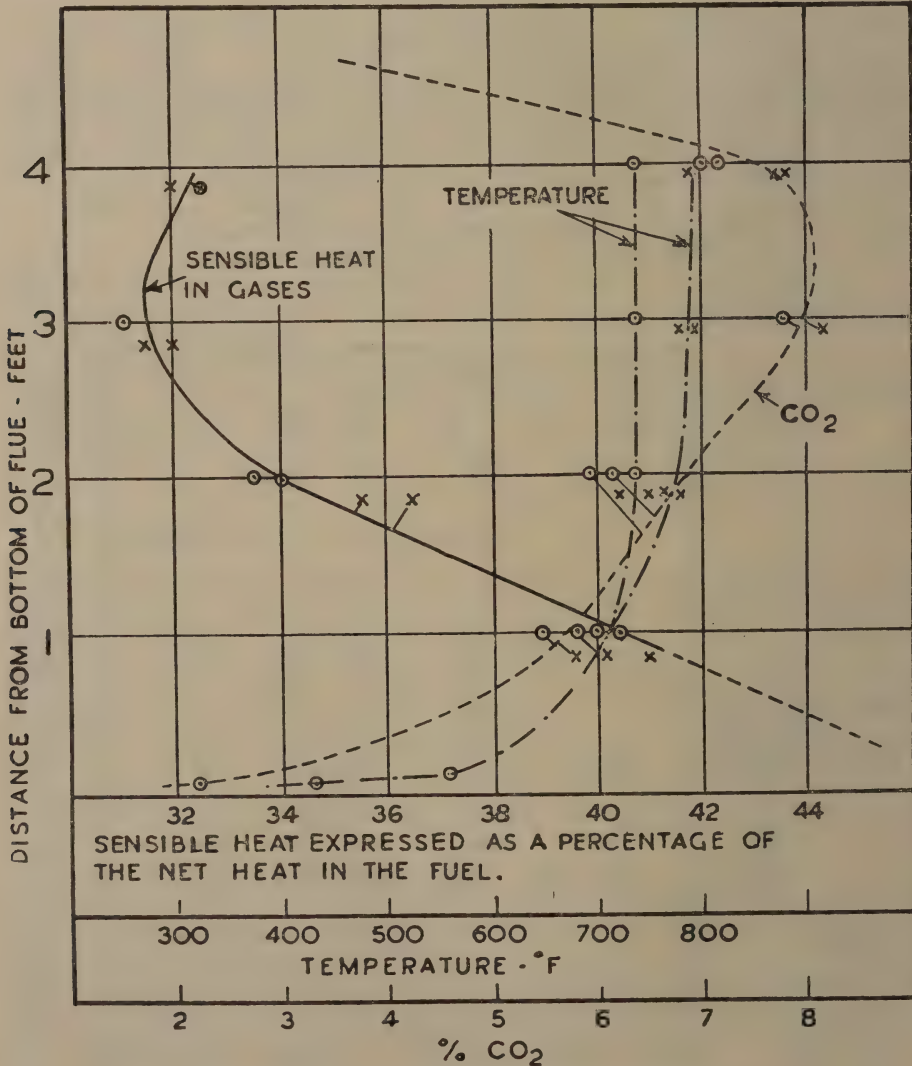


Fig. 19. Stratification of gases in a boiler flue.

the case of larger pipes and flues, however, this presumption will not necessarily hold, and the fact that the flow is in the “turbulent” region is no indication that stratification will not persist.

As a result of stratification, stock in furnaces may be immersed in gases of a temperature different from the average that was anticipated, measurements of temperature in flues may be very misleading unless the whole cross-section of the flue is explored, and the CO₂ content of the flue gases may vary in different parts of the flue.

In large flues two effects are always operative: the natural buoyancy of the gas, which tends to give separation of the heavier and lighter constituents in so far as such diffusion is not interfered with by turbulence, and the setting up of secondary effects due either to heating or to cooling of the gases by the flue walls. Attempts have been made to correlate the depth of a stream of hot gas flowing into a large duct from a smaller one on the basis of applying the analogy of water flowing over a weir, conditions being inverted when hot gas flows into a cold one.

Fig. 18 shows the temperature distribution in a boiler flue at the outlet from the economiser with the deflectors open, and indicates that a single temperature reading at this position would be quite unreliable as an indication of the true temperature of the gases. Fig. 19 shows an even more striking example of differences in temperature and CO₂ content occurring in a boiler side flue 5 feet deep by 1 foot 6 inches wide, the temperature and CO₂ contents being recorded from top to bottom.

The maximum content of sensible heat in the gases flowing in the flue is shown to occur towards the top of the flue, and it is apparent that in this zone there is a greater flow of the products of combustion than in the lower parts of the flue. The temperatures were measured with bare thermocouples of 18G, and would, therefore, indicate a temperature more nearly approaching the true temperature of the gas than would be found with the usual type of rod pyrometers, giving readings influenced by radiation from the adjacent hot surfaces of the flue.

Two further examples may be cited. A main chimney flue for a coke oven plant, fired by blast furnace gas, showed the following variations:

<i>Depth from top of flue</i>	<i>Temperature</i>	<i>Depth</i>	<i>Composition</i>	
			CO ₂	O ₂
6 in.	317° C.			
1 ft. 6 in.	421° C.	1 ft.	19·8%	4·2%
2 ft. 6 in.	317° C.			
3 ft. 6 in.	301° C.	3 ft.	19·0%	4·6%
4 ft. 6 in.	290° C.			
5 ft. 6 in.	286° C.	5 ft.	19·6%	4·0%
6 ft. 6 in.	283° C.			
7 ft. 6 in.	281° C.	7 ft.	19·0%	4·6%

Flue depth: 8 feet. Temperature recorder at 3-ft. position: 309° C.
True average temperature: 300° C. Cold velocity about 10 ft./sec.
Hot velocity about 20 ft./sec.

An example of stratification due to converging streams of flue gases of different composition derived from coke oven gas (combined velocity at 60° F. = 10 feet per second) is as follows:

Position	Bottom	4 in. up	8 in. up	12 in. up	16 in. up (top)
CO ₂ ..	6.5%	6.8%	8.8%	7.9%	6.0%
Temperature	400° C.	445° C.	498° C.	490° C.	420° C.

The above examples illustrate the extent to which stratification can occur and persist in boiler and furnace waste gas flues, and show the necessity for traversing if a true average temperature or sample for analysis is required.

When making use of a traverse to obtain the mean condition, the various values obtained must be weighted to take into account such conditions as variation of velocity of the gas at the different sampling points. Besides the effect of stratification mentioned above on the assessment of temperature or chemical composition, a direct effect is sometimes met with in the form of uneven heating of the furnace charge. The remedy there is to try to eliminate the cause.

MEASUREMENT OF FLUID FLOW IN PIPES AND DUCTS

The practical applications of fluid flow measurement in pipes and ducts (running full) are based on Bernoulli's theorem (see page 195). Either the dynamic pressure due to the velocity of the fluid is measured (as in the case of the pitot tube) or the change of pressure caused by a throttling device (nozzle, orifice plate, or Venturi tube).

Fluid flow is most commonly measured by orifice plates in pipes and by pitot tubes in ducts; it is these methods that are discussed here. Measurement of flow by weirs is discussed in Chapter 27.

Pitot Tubes

The *pitot tube* consists of a tube with an open end placed in a direction to face a stream of fluid. The pressure created in the tube is the sum of the static pressure and the velocity pressure. Means must also be provided for simultaneous measurement of the static pressure. This may be a simple connection in the wall of the main or may be incorporated in the pitot tube itself.

The difference between the static pressure and the total pressure is the velocity pressure as illustrated diagrammatically in Fig. 20. The velocity

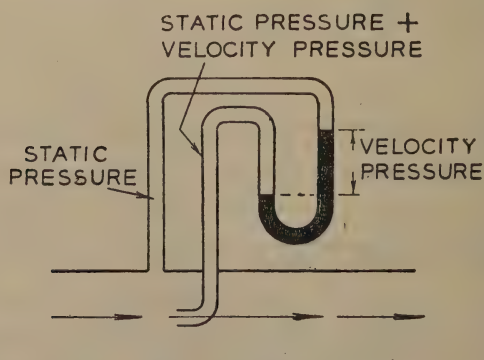


FIG. 20. Pitot tube.

(Reproduced from "Principles of Chemical Engineering," by W. H. Walker, W. K. Lewis and W. H. McAdams (McGraw-Hill).)

pressure expressed as the head of the fluid under consideration gives the velocity head, $\frac{\Delta P}{w}$, and hence the velocity V , from the formula:

$$V = \sqrt{\frac{2g \Delta P}{w}} \dots \dots \dots (30)$$

where w is the specific weight of the fluid.

For liquids this may be put in the form $V = \sqrt{2gH}$ (30a)
where H is the head of the liquid being measured.

For gases $V = 18.29 \sqrt{\frac{h}{w}}$ ft. sec. (30b)

where h is expressed in inches of water and w in lb./cu.ft. under the conditions of measurement.

The pitot tube is used where there must be no appreciable pressure loss or restriction to flow. It can usually be inserted through a small hole in the pipe wall without the necessity for shutting down the main.

The differential produced is much smaller and is less steady than with orifices, nozzles and Venturi tubes. Also, as the pitot tube and static pressure connection are liable to be choked, encrusted or obstructed with any solid matter in the fluid unless special care is taken, the measurement tends to be less accurate than that obtainable from a throttling device. As the flow is rarely uniform across a main (see Stratification, page 227) and as only one filament of the stream is being measured, it is necessary to make a cross-section traverse of the stream in order to relate the readings to average velocity.

The methods of making a traverse in circular and rectangular ducts are detailed in B.S.1042. The cross-section is divided into a number of sections of *equal area* and the average differential in each area is measured. The average velocity head of the fluid is computed by averaging the *square roots* of the velocity heads in the areas, and thus the average velocity of the fluid in the duct, may be obtained from Equation 30.

Provision must be made for a continuous indication of the rate of flow; if this does not remain constant while the velocity head readings are being taken, each reading must be corrected to compensate for variations of flow. This is most conveniently done by measuring the differential on a second, or a "control", pitot tube placed at a position from which it is not moved during the test. Readings are taken simultaneously on the traversing pitot tube and the "control" and each traverse reading is multiplied by the ratio

$$\frac{\text{Basic differential on "control"}}{\text{Differential on "control" at moment of reading traversing pitot tube}}$$

The basic differential referred to in this expression may be any convenient value within the range of the instrument.

The fixed pitot tube may subsequently be used for continuous measurement of flow once the ratio of mean velocity to velocity at the pitot tube has been established. If there are wide variations in the total flow through the system, the ratio of mean velocity to the velocity at any one point is liable to vary; a fixed pitot tube should not be used for continuous indication under these conditions.

In long pipes (i.e. where the pipe is straight for 50 diameters or more) the ratio:— $V_{\text{mean}} : V_{\text{centre}}$ varies with the Reynolds' Number (see Fig. 11).

An example in the use of a pitot tube to calculate the rate of flow of a gas is given on page 244.

ORIFICE PLATES

The *orifice plate* is an accurate and convenient means in general use for metering flowing liquids, gases and vapours at any pressure and temperature.

The two types of orifice plates considered differ only in respect of the position of the pressure tapings. It is recommended that where possible corner tapings be used and the employment of D and D/2 tapings be limited to positions where it is difficult to obtain the necessary space for insertion of an orifice with corner tapings. (See Fig. 29 below.)

Fig. 21 shows diagrammatically the construction of an orifice with corner tapings where the tapings are directly inserted in the pipe—this being applicable to large size pipes—and Fig. 22 shows a means of combining the orifice plate with a carrier which incorporates the corner tapings.

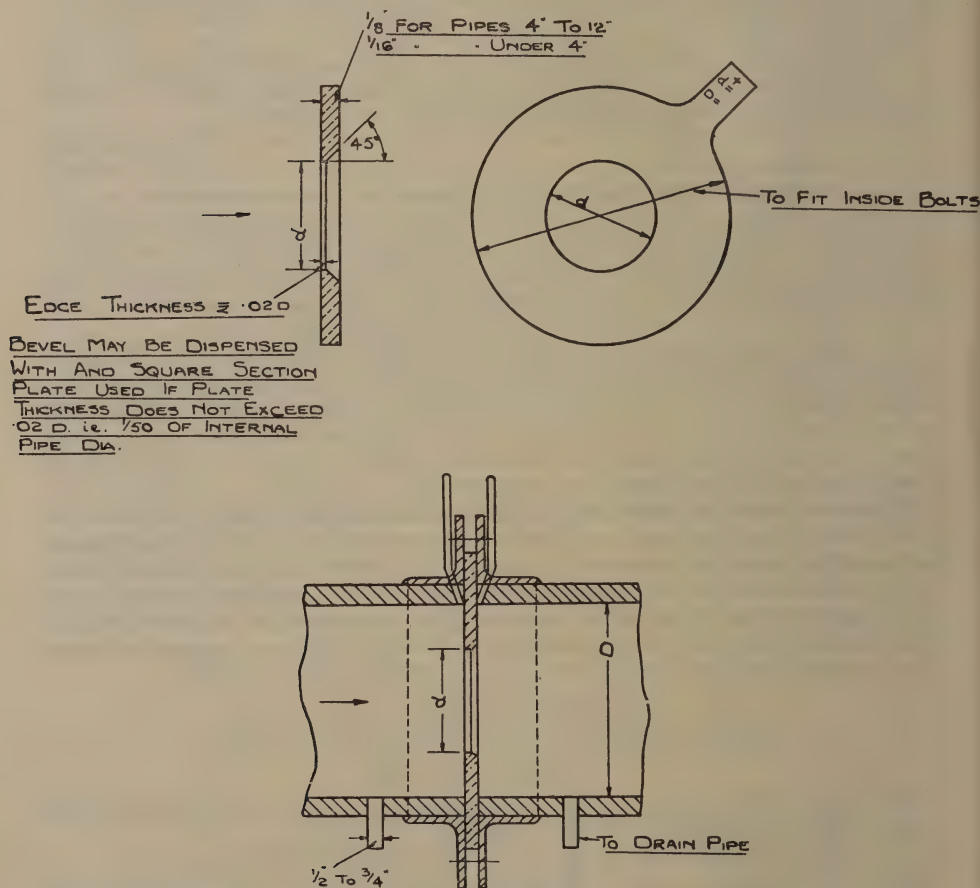


FIG. 21. Construction of an orifice plate.

(Reproduced from "Fuel Saving in the Iron and Steel Industry," by permission of the Iron and Steel Industrial Research Council.)

CARRIER RING FOR ORIFICE PLATE
STEAM MEASUREMENT

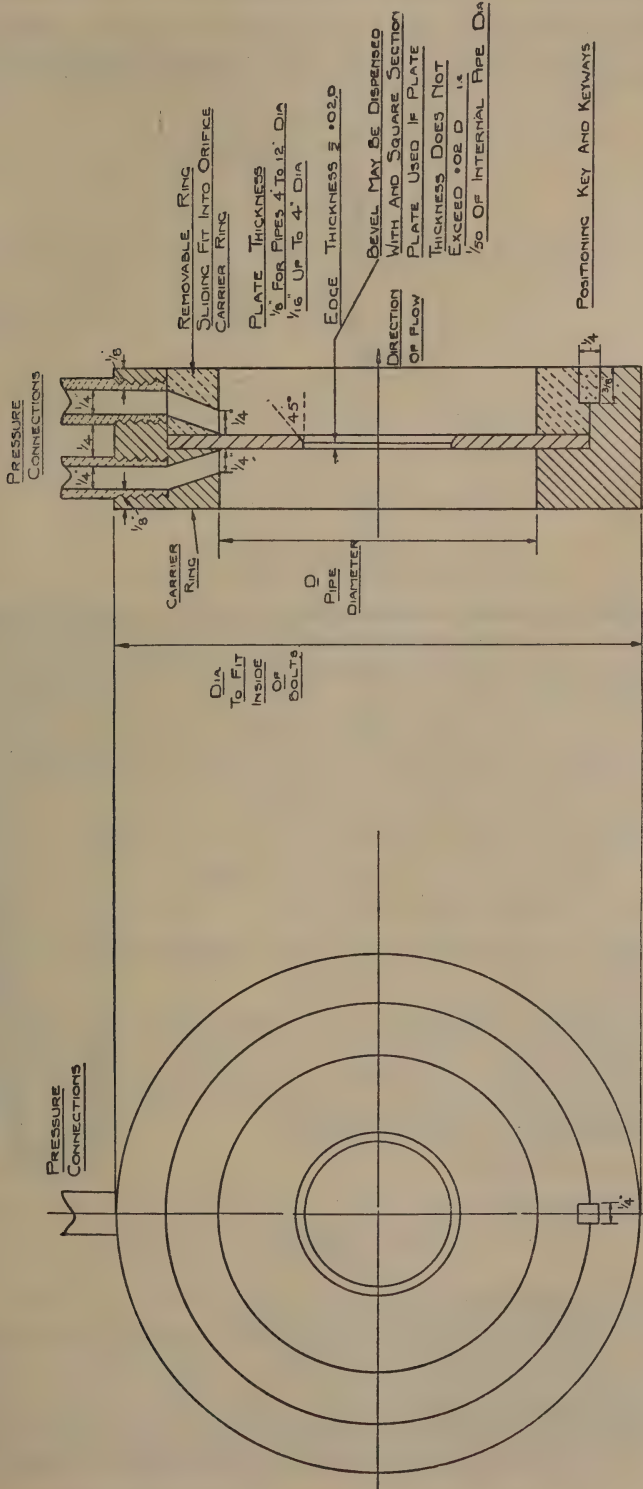


FIG. 22. Construction of an orifice plate.
(Reproduced from "Fuel Saving in the Iron and Steel Industry," by permission of the Iron and Steel Industrial Research Council.)

If an orifice be inserted in a pipe line as in Fig. 23, a pressure drop is caused and in this way a portion of the static head is converted into velocity head in the restricted section. By observing the decrease in static pressure (indicated

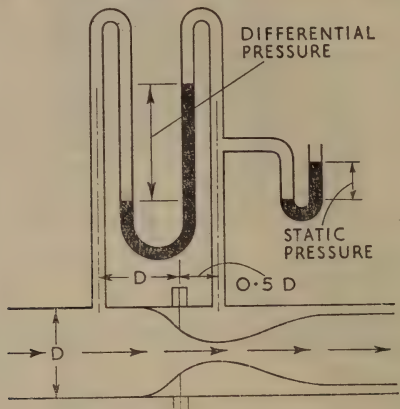


FIG. 23. Orifice plate with gauge.
(Adapted from " Principles of Chemical Engineering.")

by a differential gauge and known as the differential pressure) caused by the increase in fluid velocity the rate of flow can be calculated from Equation 3. Assuming that the pipe is running full and, for the moment, that no expansion of the fluid takes place, then

$$\sqrt{V_2^2 - V_1^2} = \sqrt{2gH}$$

V_2 being the velocity at the throat, V_1 the velocity in the pipe and H the pressure drop as head of the fluid under consideration.

By expressing V_1 in terms of V_2 , the equation becomes:

$$V_2 = \sqrt{\frac{1}{1-m^2}} \sqrt{2gH} = E \cdot \sqrt{2gH}$$

where m is the ratio of orifice or throat area to pipe area and $E = \sqrt{\frac{1}{1-m^2}}$, is known as the *velocity of approach* factor.

In practice the flow is less than that given by the above equation on account of friction loss, and in the case of the orifice plate on account of contraction of the stream after the orifice (*vena contracta*). The discrepancy is allowed for by introducing a basic coefficient of discharge C , variable with the ratio m , resulting in the flow equation:

$$V_2 = CE\sqrt{2gH} \quad \dots \dots \dots (31)$$

This may be re-written:

$$V_2 = CE \sqrt{\frac{2g\Delta P}{w}}$$

in which ΔP = pressure difference in lb./sq.ft.
and w = specific weight of fluid under working conditions at upstream tapping in lb./cu.ft.

This may be converted into formulae for weight or volume flow. For compressible fluids, an expansion correction factor, ϵ , is inserted to allow for the change of density between the two sides of the orifice; for liquids $\epsilon=1.0$.

Weight Units

$$W(\text{lb./hr.})=1273\text{ CE}\epsilon d^2\sqrt{wH'}\quad\quad\quad(32)$$
$$=1273\text{ CmE}\epsilon D^2\sqrt{wH'}\quad\quad\quad(32a)$$
$$\text{or} = 359\text{ CE}\epsilon d^2\sqrt{wh}\quad\quad\quad(32b)$$
$$= 359\text{ CmE}\epsilon D^2\sqrt{wh}\quad\quad\quad(32c)$$

Volume Units (volume rate of flow under working conditions)

$$Q(\text{cu.ft./hr.})=1273\text{ CE}\epsilon d^2\sqrt{\frac{H'}{w}}\quad\quad\quad(33)$$
$$=1273\text{ CmE}\epsilon D^2\sqrt{\frac{H'}{w}}\quad\quad\quad(33a)$$
$$\text{or} = 359\text{ CE}\epsilon d^2\sqrt{\frac{h}{w}}\quad\quad\quad(33b)$$
$$= 359\text{ CmE}\epsilon D^2\sqrt{\frac{h}{w}}\quad\quad\quad(33c)$$

In these formulae, *d* is the diameter of the orifice in inches, *h* is the differential pressure expressed as inches water gauge and *H'* is the differential pressure when this is read as inches mercury under water. The expression “under water” means that the tubes above the mercury are filled with water. The additional weight of this water in the limb in which the mercury stands lower must be taken into account (Fig. 24), e.g. when reading manometers or

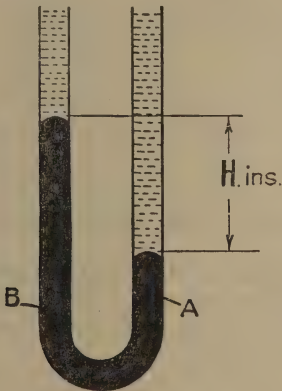


FIG. 24. Mercury gauge under water.

Since mercury in limb A has an additional pressure of *H* in. w.g. upon it above the water pressure in limb B, the true pressure is approximately :

$$H' = H - \frac{H}{\text{sp. gr. of Hg.}} \text{ in. Hg.}$$

$$\text{or } h = 12.6 \times H' \text{ in. w.g.}$$

NOTE: 12.6 = 13.6 – 1, 13.6 being the s.g. of mercury and 1 being that of water.

calibrating float-type meters. In the case of ring-balance meters, it should be noted that the deflection of the ring is independent of the density of the filling and covering liquids.

The value of the coefficient of discharge *C* varies with the ratio of the orifice area to the pipe area and also with the type of pressure tapping used as shown in Table 8 below. It is also affected, but to a lesser extent, by the value of *Re* for the fluid and by the diameter of the main. When great accuracy is required and *Re* is less than 500,000, and if the diameter of the main is below 6 in. reference should be made to B.S. 1042⁵. Otherwise values of *C* tabulated below will give results within practical limits of accuracy.

TABLE 8
RELATION BETWEEN CmE, m, AND C FOR CORNER, AND
D AND D/2 TAPPINGS (ABSTRACTED FROM B.S. 1042)

CmE	Corner tappings		D and D/2 tappings	
	m	C	m	C
0.125	0.2030	0.603	0.2027	0.604
0.150	0.2410	0.604	0.2396	0.607
0.175	0.2777	0.605	0.2770	0.608
0.200	0.3138	0.605	0.3126	0.608
0.225	0.3487	0.605	0.3470	0.608
0.250	0.3817	0.605	0.3802	0.608
0.275	0.4146	0.605	0.4122	0.607
0.300	0.4447	0.604	0.4437	0.607
0.325	0.4750	0.603	0.4725	0.606
0.350	0.5024	0.602	0.4998	0.606
0.375	0.5303	0.599	0.5257	0.606
0.400	0.5560	0.598	0.5509	0.606
0.425	0.5817	0.594	0.5733	0.607
0.450	0.6055	0.591	0.5953	0.607
0.475	0.6287	0.588	0.6153	0.608
0.500	0.6506	0.583	0.6346	0.609
0.525	0.6724	0.578	0.6517	0.610
0.550	0.6921	0.574	0.6682	0.612
0.575	—	—	0.6831	0.614
0.600	—	—	0.6964	0.617

The need to use the correction factor ϵ for compressible fluids will depend on the accuracy required. The approximate errors introduced by omitting the correction are as follows :

Differential pressure as percentage of absolute pressure	Error per cent. fast
i.e. $\frac{(P_1 - P_2)}{P_1} \times 100$	
1.05	negligible
1.25	0.5
2.50	1.0
5.00	2.0

If it is necessary to obtain the value of ϵ , reference should again be made to B.S. 1042.

The orifice diameter required for given conditions of flow and differential pressure may be obtained by first determining the value of CmE from the formulae given below. The corresponding value of m is read from Table 8. Orifice diameter equals $D\sqrt{m}$.

Weight units

$$CmE = \frac{W}{1273\epsilon D^2 \sqrt{wH}}, \quad \dots \dots \dots (34)$$

$$\text{or } = \frac{W}{359\epsilon D^2 \sqrt{wh}} \quad \dots \dots \dots (34a)$$

Volume units

$$CmE = \frac{Q \sqrt{w}}{1273\epsilon D^2 \sqrt{H}}, \quad \dots \dots \dots (35)$$

$$\text{or } \frac{Q \sqrt{w}}{359\epsilon D^2 \sqrt{h}} \quad \dots \dots \dots (35a)$$

CORRECTION FACTORS FOR APPLICATION TO METER READINGS

A manometer or meter will have been calibrated in units of flow for a specified density of the fluid (see note below). When the fluid is metered at a different density (due to change in pressure, temperature, or composition, e.g. of a gas) the correct flow can be obtained by multiplying the flow as read (i.e. based on calibration conditions) by a correction factor F .*

When the flow units are weights (e.g. lb./hr., as for steam and liquids),

$$F = \sqrt{\frac{w_m}{w}}$$

The suffix m refers to the new metering conditions for which the correction F is required. Correction factors for steam may be read from curves given in Figs. 25-28.

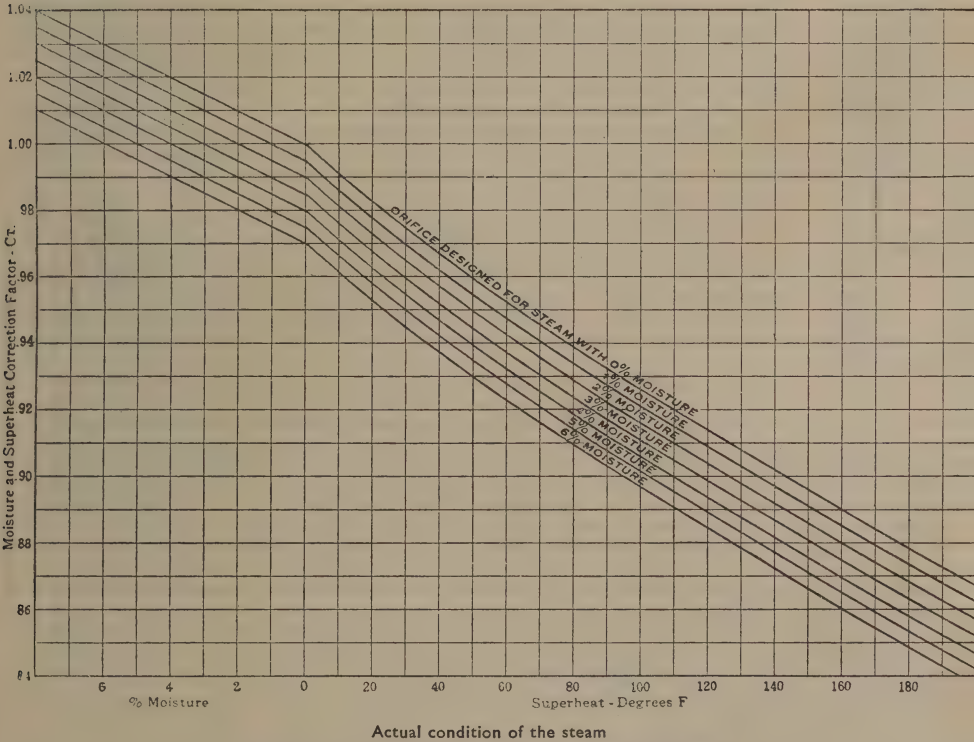


FIG. 25. Correction factors for steam meters.

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When the flow is expressed in volumes (e.g. cu.ft./hr. as for air, gases, vapours) *under working conditions*, the general formula is

$$F = \sqrt{\frac{w}{w_m}}$$

For dry gas or dry air this may be evaluated from the expression

$$F = \sqrt{\frac{G \times T \times P_m}{G_m \times T_m \times P}}$$

* A partial exception is when a meter is fitted with a pressure compensating device that automatically adjusts the meter readings for changes in density caused by change in upstream pressure of the fluid (e.g. steam, compressed air).

Correction factors for steam. Orifices designed for superheat or moisture content shown by curve.
 $\text{Weight (in lb. per hour)} = \text{Meter reading} \times \text{Constant} \times C_p \times C_r$ where
 C_p = Pressure correction factor.
 C_r = Superheat or moisture correction factor.
 Example: Temperature correction for a meter designed for 190° superheat but used at actual average operating conditions of 120° superheat correction factor = 1.045 as shown.

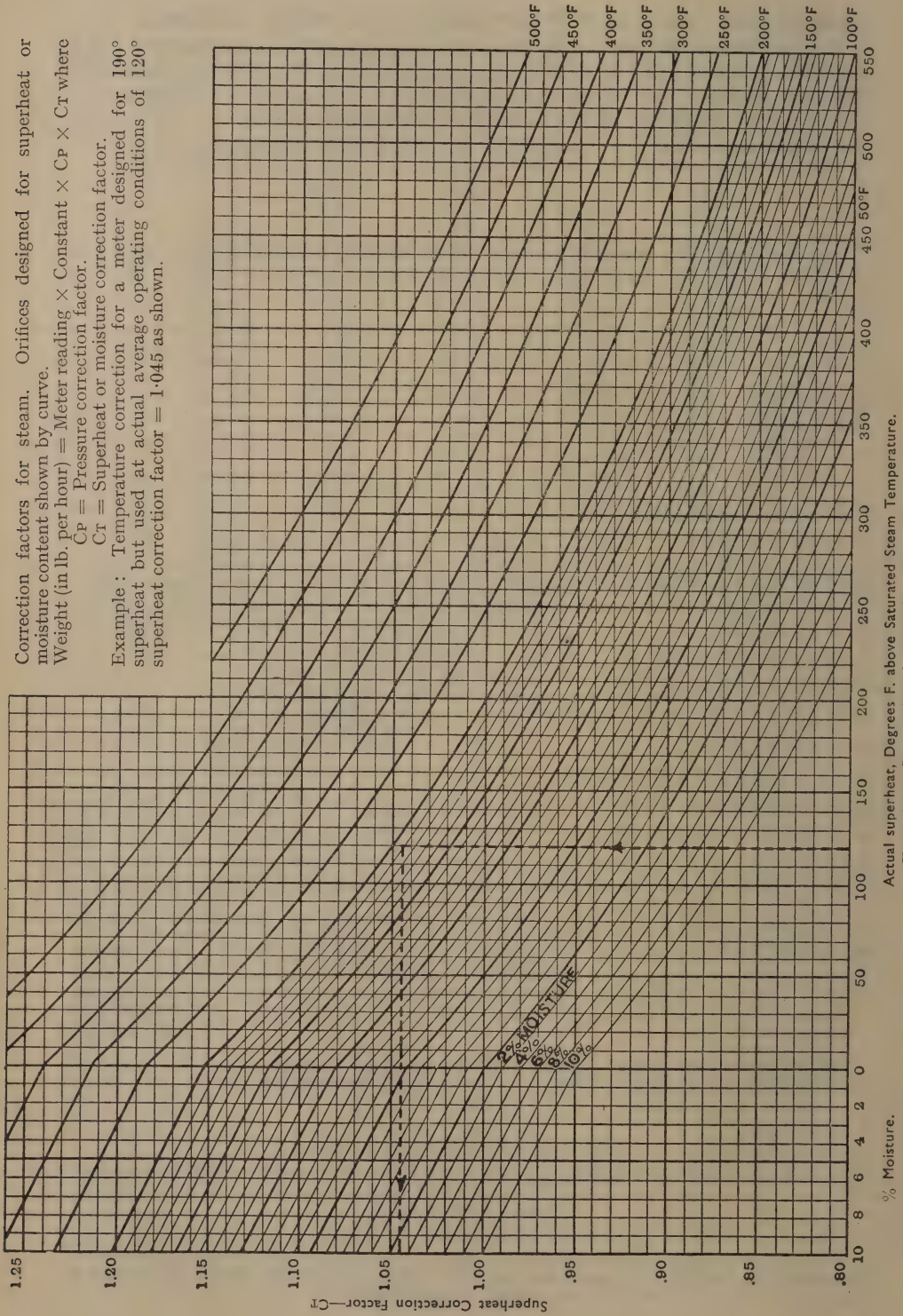


FIG. 26. Correction factors for steam meters.

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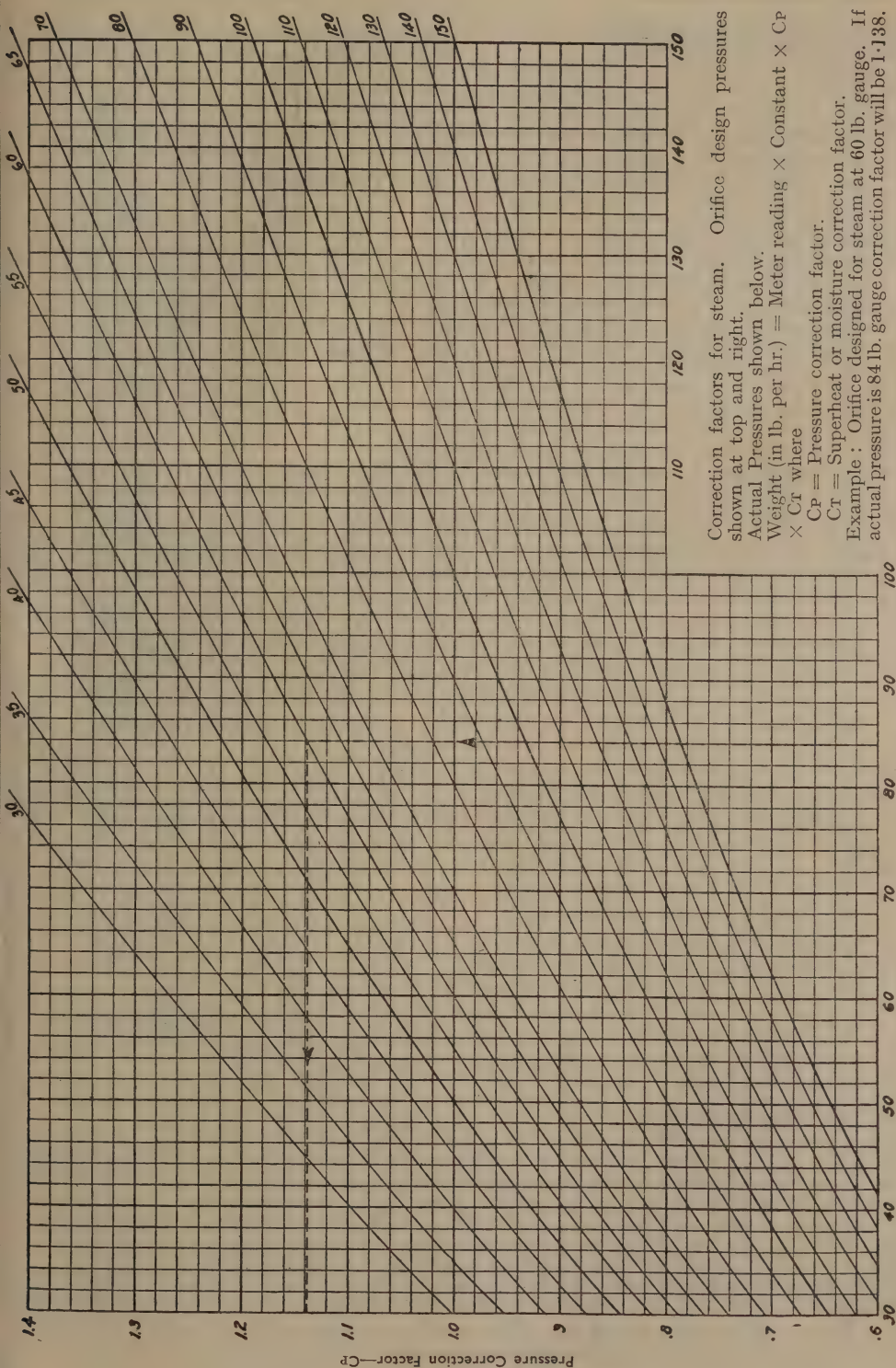


FIG. 27. Correction factors for steam meters.

(Reproduced from "Fuel Saving in the Iron and Steel Industry" by permission of the Iron and Steel Industrial Research Council.)

For moist air or gas, at temperatures in the neighbourhood of atmosphere,

$$F = \sqrt{\frac{G \times T \times (P_m - 0.378 P_{wm})}{G_m \times T_m \times (P - 0.378 P_w)}}$$

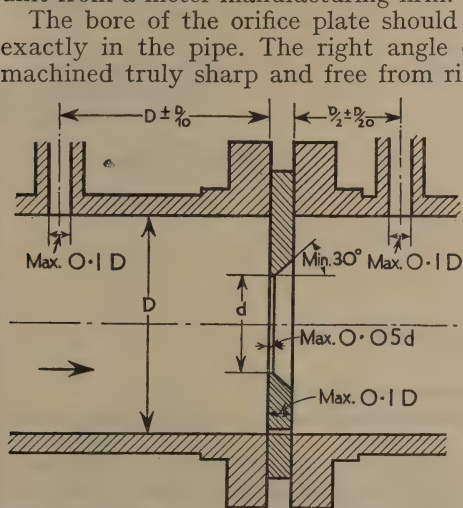
In these formulae, *w*, *P*, *P_w* and *T* refer to specific weight, upstream pressure, pressure of water vapour and temperature of the moist gas and *G* to the specific gravity of dry gas, all related to conditions for which the meter was calibrated.

It should be noted that these correction factors refer only to volumes under working conditions. For correction factors when the meter is calibrated in terms of gas under standard conditions of temperature, pressure and moisture content—such as S.T.P. (60° F. 30" Hg., saturated) or N.T.P. (0° C., 760 mm. Hg. dry), reference should be made to revised B.S. 1042 for the appropriate factors, as well as to formulate for converting volume under working conditions to standard volume.

INSTALLATION DATA

(a) *General.* The basic design data covering the measurement of flow by orifice plates applies in general to all types of fluid.

An orifice may be used in any pipe provided that *m*, the ratio of orifice area to pipe area, does not exceed 0.7 and *d*, the orifice diameter, is not less than 0.25 inch. For pipe diameters less than 2 inches, it is preferable to order a short length of pipe fitted with the pressure differential device as a complete unit from a meter manufacturing firm.



result in serious errors. Fig. 29 shows a British Standard orifice plate fitted in a pipe with *D* and *D/2* pressure tapplings. The orifice plate must be thick enough to withstand the differential pressure without distortion.

The pressure connections should not project into the pipe; any projections or burrs should be filed off. It is equally important that jointing material does not protrude into the bore of the pipe. This can be avoided by cutting the jointing material with a hole 1/2 inch larger than the internal pipe diameter. Riveted flanges should also be avoided as the projecting rivets may introduce large errors

FIG. 29. Orifice plate with carrier ring for *D* and *D/2* tapplings.

in measurement. There should also be no change in pipe diameter in the immediate vicinity of the orifice. It is important that the position of the tapping holes in relation to the orifice, as shown in Figs. 21 and 22 for corner tapplings be adhered to.

The pressure pipes between the tapplings and point of measurement must be maintained at equal temperature. They must be laid with adequate slope (not less than 1 in 20) to ensure drainage of water from these pipes when metering gas or air, or venting of air when metering steam or liquids.

In the case of an orifice which is to be installed in a horizontal main, a drain

or vent hole (or diameter not greater than $0.1 d$, or $\frac{3}{16}$ inch, whichever is less) should be drilled in the orifice at a radius just short of the pipe radius. The orifice should be installed with the drain hole on the bottom when metering steam or gas to prevent accumulation of water on the upstream side, or with the hole on the top when metering liquids to prevent accumulation of air.

(b) *Steam*. When metering steam the following special precautions should be observed:

1. An equal head of water must be maintained in each pressure connection to the meter. To ensure this, condensing chambers are installed close to the orifice tappings. In the case of horizontal mains, these tappings are best made in the side of the pipe, level with the axis, with short horizontal connections to the condensing chamber inlets. In the case of vertical pipes the two chambers must be installed at the level of the upper orifice tapping, one chamber being connected to this tapping by a short horizontal pipe. The other chamber must be connected to the lower tapping by a pipe of sufficient slope and at least $\frac{1}{2}$ inch diameter to ensure that any water collecting in this connection will drain freely back into the main leaving a free steam space—otherwise a false head would be shown on the meter.

These condensing chambers can easily be made from standard pipe fittings; a simple type is illustrated in Fig. 30. The chambers should have sufficient volume and condensing capacity to ensure that the

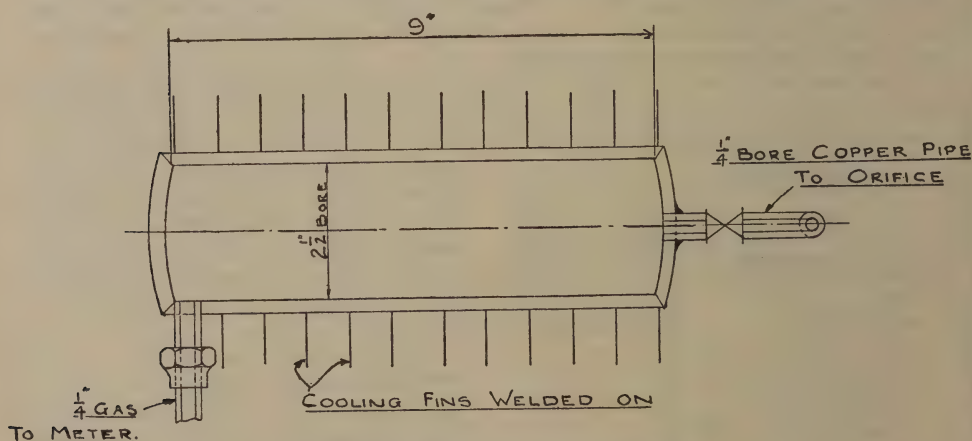


FIG. 30. Steam condensation chamber.

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- pipes and vessels remain full of water up to the level of their inlets and that the water displaced by the measuring instrument in moving from maximum to minimum reading or vice-versa does not affect the maintenance of an equal head in both pipes.
2. The pipes transmitting the pressure from the orifice to the manometer or recorder must be free from leaks, a small leak (even though it may appear insignificant) will cause serious errors.
 3. There must be no air locks in the pressure pipes. Air is removed from the pressure pipes, when first connecting up to the manometer or recorder, by slacking off the unions at the instrument, blowing steam through to expel the air from the pipes, and finally tightening up the unions. Provision is sometimes made for bleeding air from the system by valves incorporated in the measuring instrument.

(c) *Low Pressure Gases.* For relatively large gas mains the design shown in Fig. 31 is usually the most appropriate. Since the allowable pressure loss when measuring low pressure gas is generally small, special precautions are necessary to ensure accurate measurement of the differential pressure. Fig. 31

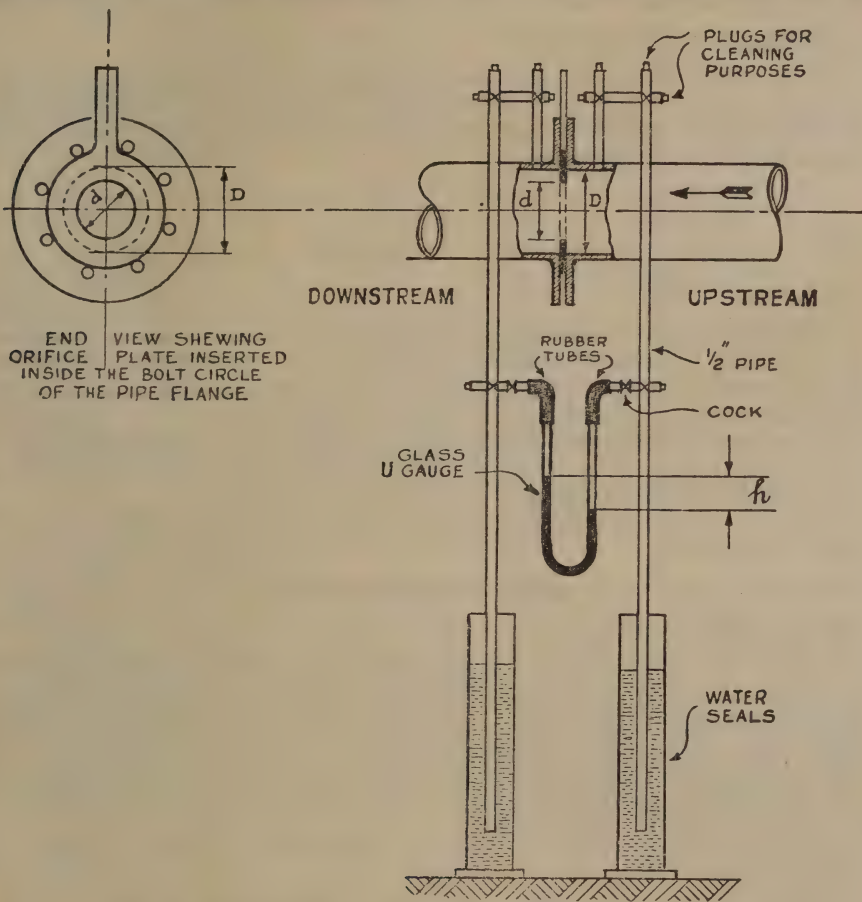


FIG. 31. Arrangement of orifice plate for gas measurement.

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indicates one arrangement embodying a glass U-tube manometer with water or other suitable liquid as the measuring fluid. For more accurate readings an inclined gauge would be used. It will be noted that precautions are necessary to prevent condensate from entering the U-tubes.

ORIFICE LOCATION

The orifice should be placed in a straight length of pipe free from bends, valves, etc. The upstream distance from the orifice plate must be adequate to eliminate the effect of any disturbance of the flow due to any of the causes described above. The same applies to the downstream distance, but to a much lesser degree.

The minimum length of straight pipe preceding the orifice should in no circumstances be less than 8-10 diameters, and the minimum length down-

stream 3-5 diameters, without involving serious errors. For more precise information reference should be made to B.S.1042.

Where the orifice plate is bevelled on one side, care must be taken that it is correctly inserted with the bevel facing downstream. With the bevel facing upstream the readings obtained would be low; even as much as 15-20 per cent.

PERMANENT PRESSURE LOSS

When determining the permissible maximum differential pressure it is necessary to know the permanent pressure loss that the orifice introduces into the system. This loss varies according to the ratio of the orifice to the pipe diameter, as here shown.

$\frac{\text{Orifice diameter, i.e. } Nm}{\text{Pipe diameter}}$	0.2	0.3	0.4	0.5	0.6	0.7	0.8
<i>Permanent pressure loss as a percentage of differential pressure</i>	95	89	80	72	62	52	37

PULSATING FLOW

The orifice method described provides an accurate method of measurement of what may be termed steady flows, that is, when the indicating gauge or meter is able to follow all changes of velocity. This, however, does not apply when the orifice is placed near a source of pulsation such as a reciprocating engine, when serious errors in the meter readings may be introduced due to velocity pulsations which cannot be followed by the meter or which are unreadable without damping.

Whenever a pulsating flow has to be measured it is advisable to consult the meter manufacturer.

PRACTICAL EXAMPLES

USE OF PITOT TUBE

A pitot tube is inserted in a 12-inch diameter gas main carrying blue water gas (sp.gr. 0.55, dry gas/dry air), along the centre line of the main. The differential pressure is registered by a water-filled U-tube attached to the two connections and inclined to the horizontal at 10 : 1; the reading is 0.5 in. The pressure in the gas main is 24 in. w.g. and the barometric pressure is 29 in. Hg. and the gas temperature 80° F. What is the rate of flow expressed as cu.ft./hour at 60° F. and 30 in. Hg.?

Assume specific weight of dry air = 0.08071 lb./cu.ft. at 32° F. and 29.92 in. Hg.

It is necessary first to determine the specific weight of the saturated gas (applying the laws of partial pressures under the existing conditions of temperature and pressure) as follows:

(a) Saturation pressure at 80° F. = 1.035 in. Hg (from steam tables).

(b) Total pressure in the main = $29 + \frac{24}{13.6}$ i.e. 30.76 in. Hg.

Therefore weight of dry gas in 1 cu.ft. saturated gas at 80° F.

$$= 0.55 \times 0.08071 \times \frac{492}{540} \times \frac{(30.76 - 1.035)}{29.92} = 0.0402 \text{ lb.}$$

(c) Approximate weight of water vapour in 1 cu.ft. saturated gas at 80° F.

$$= 0.0502 \times \frac{492}{540} \times \frac{1.035}{29.92} = 0.0016 \text{ lb.}$$

(0.0502 is the weight of water vapour per cu.ft. at 32° F. and 29.92 in. Hg. The temperature and pressure corrections are made on the assumption that the water vapour behaves as a perfect gas).

(d) Therefore sp.wt. of saturated gas under actual flow conditions
 $= (b) + (c) = (0.0402 + 0.0016) = 0.0418 \text{ lb./cu.ft.}$

The reading of 0.5 in. on the U-tube corresponds to a pressure head of 0.05 in. w.g. Since 1 in. w.g. = 5.2 lb./sq.ft., the head of gas equivalent to 0.05 in. w.g. is

$$\frac{5.2 \times 0.05}{0.0418} \text{ ft., i.e. } 6.22 \text{ ft.}$$

From Equation 30a $V = \sqrt{2 \times 32.2 \times 6.22} = 20 \text{ ft./sec.}$

This is the velocity at the centre of the main, and since absolute viscosity in c.g.s. units is 0.000165 poise (see Table 2) then Reynolds' Number

$$\frac{\rho D V_{\text{centre}}}{\eta} = \frac{0.0418 \times 1.0 \times 20}{0.000165 \times 0.0672} = 78,350.$$

Hence from Fig. 11 the ratio $V_{\text{mean}} : V_{\text{centre}} = 0.81$;
 therefore average velocity $= 0.81 \times 20 \text{ ft./sec.}$

\therefore volume rate of flow $= 0.81 \times 20 \times \frac{\pi}{4} \times 3,600 \text{ cu.ft./hr. (D = 1.0)}$

$= 45,800 \text{ cu.ft./hr. at } 80^\circ \text{ F. and } 30.76 \text{ in. sat.}$

$= 45,800 \times \frac{520}{540} \times \frac{(30.76 - 1.035)}{(30 - 0.521)} \text{ cu.ft./hr. at } 60^\circ \text{ F. } 30 \text{ in. Hg, sat.}$

(0.521 in. Hg is the saturation pressure at 60° F.)

$= 44,500 \text{ cu. ft./hr. at } 60^\circ \text{ F. and } 30 \text{ in. Hg. sat.}$

USE OF ORIFICE PLATES

The problem usually met in practical flow measurement with a differential pressure device such as an orifice plate can be stated to be as follows:

1. The determination of the rate of flow, for a specified orifice diameter and for a given or permissible differential pressure.
2. The determination of an orifice diameter required to measure the flow for a specified plant. Here it is first necessary to decide on the allowable pressure loss in the pipe line at the estimated flow rate. This applies especially to gaseous flow where the available static pressure is very often less than 6 inches w.g. and where the permanent pressure loss must be kept at a minimum.

Example A.

Superheated Steam—Calculation of Flow—Orifice with Corner Tappings.

Data:

Steam pressure $P = 150 \text{ lb./sq.in. gauge.}$
 $= 164.7 \text{ lb./sq.in. absolute.}$

Temperature of steam, $t \quad \dots \quad = 400^\circ \text{ F.}$

Specific weight, $w \quad \dots \quad = 0.340 \text{ lb./cu.ft.}$

Differential pressure, H' (under water) $\dots = 4 \text{ in. Hg.}^\dagger$

Pipe diameter, $D \quad \dots \quad = 8 \text{ in.}$

Orifice diameter, $d \quad \dots \quad = 4 \text{ in.}$

It is required to calculate W , the rate of flow in lb./hr.

For this example Equation 32a is used:

$$W = 1273 \text{ CmE } \epsilon D^2 \sqrt{w H'} \text{ lb./hr.}$$

but the correction for the expansion factor ϵ is neglected.

$$\text{Orifice ratio } d/D = 0.5, m = \frac{d^2}{D^2} = 0.25.$$

From Table 8 $\text{CmE} = 0.1561.$

$$\text{Approximate Rate of Flow, } W = 1273 \times 0.1561 \times 8^2 \times \sqrt{0.34} \times \sqrt{4} \\ = 14,840 \text{ lb./hr.}$$

For more correct rate of flow an allowance must be made for the expansion of the orifice and main due to temperature as well as for ϵ . See B.S. 1042.

Example B1.

Saturated Steam—Determination of Orifice Diameter—For Orifice Installation with Corner Tappings.

Data:

Rate of flow, W (known or assumed) ..	= 16,000 lb./hr.
Absolute pressure, P	= 134.7 lb./sq.in.
Temperature, t	= 350° F.
Specific weight, w	= 0.3 lb./cu.ft.
Permissible differential pressure expressed as inches of mercury under water, H'	= 7.0 in. Hg.†
Expansion factor, ϵ	neglected.
Pipe diameter, D	= 6 in.

It is required to determine what should be the diameter of the orifice, d .

Here Equation 34 is used:

$$\text{CmE} = \frac{W}{1273 \epsilon D^2 \sqrt{w H'}} \\ = \frac{16,000}{1273 \times 36 \times \sqrt{0.3 \times 7}} = 0.241.$$

From Table 8 $m = 0.3708$

$$\text{Hence } \frac{d}{D} = 0.609$$

Since $D = 6$ in., the orifice diameter $d = 6 \times 0.609 = 3.654$ in.

Example B2.

Saturated Steam—Data as for *B1*.

Had the use of an orifice with D and $D/2$ tappings been required, the size of the orifice would be calculated as follows:

For $\text{CmE} = 0.241$ (see example *B1* above) the value of m for orifice with D and $D/2$ tappings, from Table 8 = 0.369

$$\text{Hence } d/D = \sqrt{m} \quad \dots \quad = 0.607$$

$$\therefore \text{Orifice diameter, } d, = 6 \times 0.607 \quad \dots = 3.642 \text{ in.}$$

Example C.

Water—Calculation of Flow—Orifice with Corner Tappings.

Data:

Diameter of main, D	= 10 in.
„ „ orifice, d	= 7 in.
Temperature, t	= 90° F.
Specific weight, w , at 90° F. ..	= 62.11 lb./cu.ft.
Differential pressure H' (under water)	= 6 in. Hg.

It is required to determine the rate of flow, W lb./hr. or q gal/hr.

Equation 32a is used.

$$W \text{ lb./hr.} = 1273 \text{ CmE } D^2 \sqrt{w H'}$$

$$\text{Orifice ratio } d/D = 0.7, \text{ whence } m = 0.49.$$

† When a ring-balance type of instrument is used to measure the differential pressure, the maximum deflection of this type of instrument is expressed in inches Hg. under air (not under water).

CmE (from Table 8 corner tappings) = 0.339.

$$\begin{aligned}\text{Rate of flow, } W, &= 1273 \times 0.339 \times 100 \times \sqrt{6 \times 62.11} \\ &= 833,300 \text{ lb./hr.}\end{aligned}$$

Since 1 gallon of water at 90° F. weighs 9.961 lb.,

$$q = \frac{833,300}{9.961} \text{ i.e. } 83,650 \text{ gal./hr.}$$

If the orifice were fitted with D and D/2 tappings instead of corner tappings, CmE = 0.341 and W = 838,200 lb./hr.

Example D.

Town Gas—Determination of Orifice Diameter.

Data:

Maximum rate of flow, Q .. = 250,000 cu.ft./hr., measured under conditions of flow

Pressure of gas at upstream

tapping = 30 in. Hg.

Diameter of main, D .. = 22 in.

Temperature of gas at upstream tapping = 60° F.

Humidity = 100 per cent.

Specific gravity of dry gas relative to dry air, G .. = 0.42

Specific weight of gas under conditions of flow, w .. = 0.0342 lb./cu.ft.

Maximum differential head, h = 2.0 inches, w.g.

It is required to determine what should be the diameter, d, of an orifice with corner tappings, for these conditions.

Equation 35a is used.

$$\text{CmE} = \frac{Q\sqrt{w}}{359 \epsilon D^2 \sqrt{h}}$$

$$\text{Neglecting } \epsilon, \quad \text{CmE} = \frac{250,000 \sqrt{0.0342}}{359 \times 484 \times \sqrt{2.0}} = 0.188.$$

From Table 8 for CmE = 0.188 m = 0.296

Hence d/D = 0.544

∴ d = 0.544 × 22 = 12 in.

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CHAPTER 11

STOKING AND BOILER OPERATION

COMBUSTION AIR CONTROL

Combustion is the result of bringing fuel and air into contact, while maintaining a sufficiently high temperature to ignite the fuel. Theoretical aspects have been discussed in Chapter 8; this chapter deals with the more practical aspects and certain of the equipment used in the firing and general operation of boilers.

Movement of Air. In coal-fired boiler furnaces, except those fired with pulverized fuel (see Chapter 12), the coal is supported on a grate through which the air is caused to flow because the pressure beneath the grate is greater than that above the grate. The difference between these pressures is secured either by maintaining pressure below atmospheric above the grate, that beneath the grate remaining at approximately atmospheric level (*natural* and *induced draught*), or by raising the pressure beneath the grate by supplying air at a few inches water gauge pressure from a fan or by steam jets (*forced draught*). The required pressure differences can be secured by natural draught if the chimney is high enough, and the resistance to gas flow through the rest of the gas passages in the boiler plant is not too high, or by a fan. When the fan supplies air to the furnace under pressure it is known as a *forced draught fan*; when it is placed between the boiler and the chimney and sucks the air through the furnace it is known as an *induced draught fan*. With forced draught the pressure above the fuel bed must still be maintained slightly below atmospheric, to avoid leakage of furnace gases into the boiler house, though it can be higher than with natural or induced draught. Draught is discussed in Chapter 8.

Distribution of Air. The next problem is to control air distribution. The resistance of the fuel bed should be kept as low as possible. Since the air will take the path of least resistance, it is necessary to keep the resistance of the fuel bed as uniform as possible, otherwise the air may flow through places where there is little or no coal, or through channels where it does not come into contact with the coal. This principle of securing proper distribution of air through the fuel bed is fundamental; most of the difficulties that arise in burning solid fuel are the result of faulty distribution of combustion air. In hand firing, blowholes and thin patches may occur. The result is low boiler efficiency, with inadequate steam output. Careless firing of the fuel may leave bare patches in the corners of the grate and towards the end; a skilful fireman always guards against such occurrences.

In mechanical firing there are two distinct types of grate; *fixed grates*, from which the ashes must be removed manually, and *moving grates*, which are self-cleaning. In practically all cases the distribution of air is controlled by the evenness of the fuel over the bed, and to secure proper fuel distribution is a fundamental objective of the stoker designer; it is difficult to obtain perfect distribution when a range of fuels, differing in particle size and "stickiness", has to be handled.

With the moving grate, moreover, fuel bed resistance is certainly not constant over the whole length. Coal is moved by the grate from the front, which is charged with fresh coal, towards the rear, where the residue from burning is dumped over the end of the grate into the ash pit. During the burning process the coal loses weight and bulk; consequently the fuel bed resistance

tends to decrease. It thus becomes necessary to reduce the amount of air supplied to the rear end of the grate. At least one make of coking stoker is provided with a deflector beneath the grate to give preferential air flow to the front; some trough bar grates are so designed that the air pressure is progressively less from front to rear. With all moving grates, care must be taken to remove any build-up of clinker at the sides, otherwise rupture of the fuel bed will occur and air will leak through unused. It is desirable that the air supply to the back of any moving grate be under control. The air supply to this section of the grate should usually be kept to the minimum but it is useful to be able to supply some air at this point to prevent unburnt fuel from passing over the back of the grate.

Quantity of Air

The importance of using the right amount of air, in the right place, has been explained in Chapter 8. The use of too much air results in loss of heat in the products of combustion—and often in heavy grit emission; too little air results in smoke production, loss due to carbon in ash, and perhaps low boiler output. Steam is produced in proportion to the rate at which coal is being burnt and this, in turn, depends on the rate at which the air is supplied to it (always assuming good mixing of air and fuel). It follows that at all times the rate of burning of the coal should keep pace as closely as possible with the steam demand. To achieve this, the fireman must watch the steam flow meter closely; if there is none, he must watch the boiler pressure gauge—though this is really inadequate as a detector of steam flow—and he must be prepared to adjust the rate of coal feed and air flow through the boiler. The air flow is adjusted by opening or closing the dampers and, if mechanical draught is also used, by manipulating the draught air controls.

If the steam flow changes frequently, the dampers have to be moved frequently; consequently the fireman may tend to neglect this. Hence it is essential to have all air and damper controls *readily accessible on the firing floor*, and they should be light to handle and positive in action. In far too many cases dampers and controls are set to predetermined positions, these being marked off on the operating rod or quadrant. A more positive guide should be provided for the operator by means of instruments to indicate the performance of the boiler. Draught gauges in conjunction with gas analysers and steam flow meters, or steam/air flow meters, will permit of adequate control over damper settings and combustion air, whether the plant is provided with forced, induced or natural draught. Intelligent use of such instruments not only helps the operator to obtain the correct fuel/air ratio, but also enables him to detect and correct uneven firing conditions, fouling of heating surfaces and the ingress of extraneous air.

For the purposes of combustion, air is necessary in a boiler furnace only to provide oxygen to burn the fuel; any that enters in excess of this or does not mix with the coal, or its combustible products, is both unnecessary and undesirable, as previously mentioned. Too great an excess of air adversely affects boiler efficiency and makes unnecessary demands on the available draught. Apparent lack of draught accompanied by insufficient boiler output can often be traced to unnecessarily large excess of air and may be cured simply by reducing the air supply. A low chimney CO_2 reading will indicate excessive air, but it must then be decided whether the cause is the admission of too much air into the furnace or inleakage after the furnace.

It is, therefore, important to seal off all places in the boilers, economiser and flue system where air can enter. Starting at the front of the boiler, the joints around the furnace and the whole of any brickwork setting in which the

boiler may be contained should be examined. Leaks can be stopped with wet asbestos rope, caulked well and pointed with fireclay mixed with water containing a little sodium silicate (water glass). Continual packing with asbestos rope is liable to lead to cracking of the brickwork. Self-contained boilers (e.g. Economic) are not liable to air in-leakage since there is no external brickwork.

One method of detecting leaks is to close the dampers little by little so that, for a brief period, smoke is caused to issue through the leaks, which are then noted and attended to. Alternatively the flame of a candle or of a small oil lamp may be used, the flame being sucked into the leaky places. This operation should be carried out with the dampers in their normal positions; when blowing the flues, ash and soot will generally be blown out through faulty brickwork, and this affords another indication whether the brickwork is tight or not.

Attention must also be paid to the main flue and economiser brickwork, the damper seals, the scraper gear on the economiser, and the top of the superheater. When opportunity occurs, the brickwork should also be inspected from the inside. With Lancashire boilers particular attention should be paid to the downtake (where expansion joints are often useful) and to the seating blocks. In general, it should be noted that even sound, uncracked brickwork is quite porous and the external surfaces should be treated with bitumastic paint.

Air that enters through a leaking setting (infiltrating air) has a different effect from that of air that leaks in through a defective fuel bed or stoker front.

Infiltrated air dilutes the products of combustion after these have given up the greater part of their heat to the boiler and thus can affect heat transfer only to the less important part of the heating surface (the side flues, and to some extent the economisers). The air that enters through the combustion zone (surplus combustion air), on the other hand, affects heat transfer over the whole of the heating surface of the system. It is, therefore, more important to control the surplus combustion air than the infiltrated air. This statement must not be interpreted as meaning that infiltrated air may be neglected; all unrequired excess air should be reduced to a minimum. In any event, infiltration of air reduces the available draught and may be serious when using natural draught in particular. Fig. 1, reproduced from the report of the Shell Type Boiler and Firing Equipment (R/16) Committee B.C.U.R.A., shows quite clearly the respective effects of the two forms of excess air.

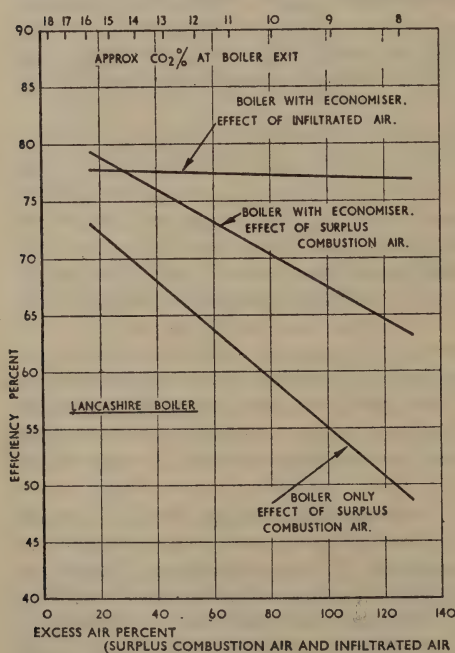


FIG. 1. Effects of excess combustion air and infiltrated air.

MECHANICAL FIRING

In recent years it has become evident that the machine can stoke a boiler better than a man. Except for some of the smallest boiler installations continuance of hand firing can hardly be justified on economic grounds. The

importance now attached to the prevention of smoke has sounded the knell of hand firing.

There are four main types of automatic stoker : (1) Chain-grate, and its variant, travelling grate, (2) Coking, (3) Sprinkler, (4) Underfeed.

Other types of firing appliances are known, but their use in Britain has not been widespread up to the present. The above four types of grate are now dealt with in further detail.

THE CHAIN-GRATE STOKER

An endless "chain" receives coal from a hopper and passes it beneath a guillotine door which regulates the thickness of the fuel bed. The fuel then passes into the furnace, gradually burning as it moves along. The ash produced is discharged over the back end of the grate, where the chain turns down and returns to the front of the grate and resumes the journey. This form of grate, invented by Juckes in 1841, is one of the oldest forms of automatic coal firing appliance.

Fig. 2 illustrates a typical chain grate applied to a shell boiler. The hopper is supplied with coal which rests on the chain link grate, the grate moves forward, passing underneath the guillotine door, which is adjustable so as to regulate the fuel bed thickness, normally about four inches though special

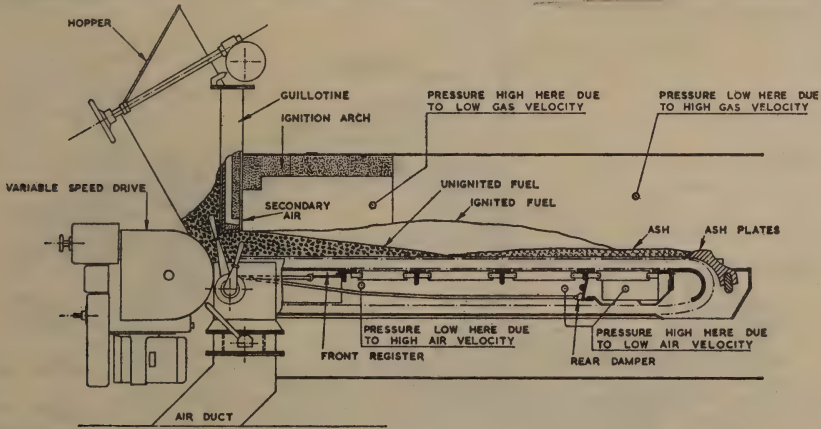


FIG. 2. Typical chain grate applied to a shell boiler.

conditions sometimes demand thicker or thinner fuel beds. Generally the larger the fuel the thicker should be the fuel bed. The ignition arch becomes heated by the burning fuel beneath it and so acts as a source of radiation to stabilize ignition. Beneath the grate a dead plate prevents air from entering the fuel bed too soon, otherwise the fuel might burn back towards the hopper. This is followed by an adjustable air register, which allows the amount of air passing through the fuel bed in the early stages of its journey to be controlled independently of the rest of the air supply. This register should be normally fully open, though it is kept closed when coke breeze or very free burning coal is being used. For the next few feet the coal moves forward above the main air supply, the latter being controlled from the main forced draught damper.

Towards the rear of the grate there is a damper, which may be used to exclude air from this part of the grate. This damper is closed when it is evident that air is leaking through the fuel bed—the evidence being a very clean ash pit and a low CO₂ content in the flue gases. The damper should be opened if there is any tendency for unburnt fuel to be discharged into the ash pit. This may be recognised by the build-up of large quantities of "coke" which continue

to burn in the pit. This sort of occurrence must be carefully avoided with all types of mechanical grates, reciprocating or travelling, since it leads not only to waste of good fuel but also to serious damage to the rear ends of the grates. The cause may lie not only in incorrect adjustment of the air controls but also in incorrect "conditioning" of the fuel with moisture. The subject of moisture conditioning is referred to later in this chapter.

For the smaller chain grate, secondary air is provided at the front end, in several cases through ports actually in the guillotine, as shown in Fig. 2. Secondary air for larger grates is generally supplied through nozzles above the fuel bed, the nozzles being fed from a wind box on the boiler front.

Mechanical stokers should not be used for firing coal bigger than, say, two inches, the upper size limit for chain grates being preferably not more than one inch. The chain grate is particularly suitable for half-inch smalls, provided these are properly wetted, to contain about $1\frac{1}{2}$ per cent. of surface moisture for every 10 per cent. of coal below $\frac{1}{8}$ in. mesh. No mechanical grate should be used with very low ash coals; less than 7 per cent. of ash may give rise to overheating. Protection of the grate bars, to prevent damage, is of very great importance in mechanical stoking owing to the expense of repairs; hence a moderate amount of ash is actually an advantage. On the other hand, very

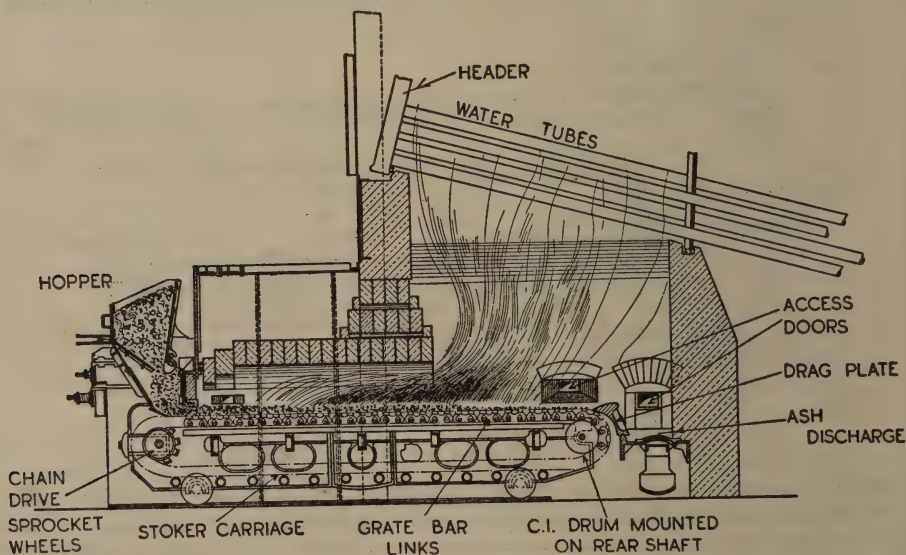


FIG. 3. Chain grate stoker applied to a water-tube boiler.

high ash coals may be difficult to burn, particularly if the fines content is high. Very strongly caking coals should, of course, be reserved as far as possible for the coking industry, but the chain grate can deal with them effectively if need be.

The chain grate is now firmly established as an appliance for firing shell boilers. Its very wide and increasing use in this field speaks for itself. More than any other type of grate, it has withstood the test of time in water-tube boilers. A "miniature" variety has been recently introduced for use with central heating boilers. A chain-grate stoker applied to a water-tube boiler is shown in Fig. 3.

THE COKING STOKER

In this type, a thick fuel bed is supplied by ram feed from a hopper on to

reciprocating grate bars which move the coal forward along the grate, on which it burns progressively until, at the end, the ash is discharged over the ends of the bars into the ash pit.

There are several types of coking stoker. Fig. 4 shows a well-known design in which the coal feed to the grate is assisted and regulated by a reciprocating ram, the stroke of which can be adjusted. The coal from the hopper is pushed by the ram on to the top of the fuel bed, which is kept in a state of ignition by air drawn through ports in a front plate. The ports serve also as poke holes through which a poker may be introduced from time to time to manipulate

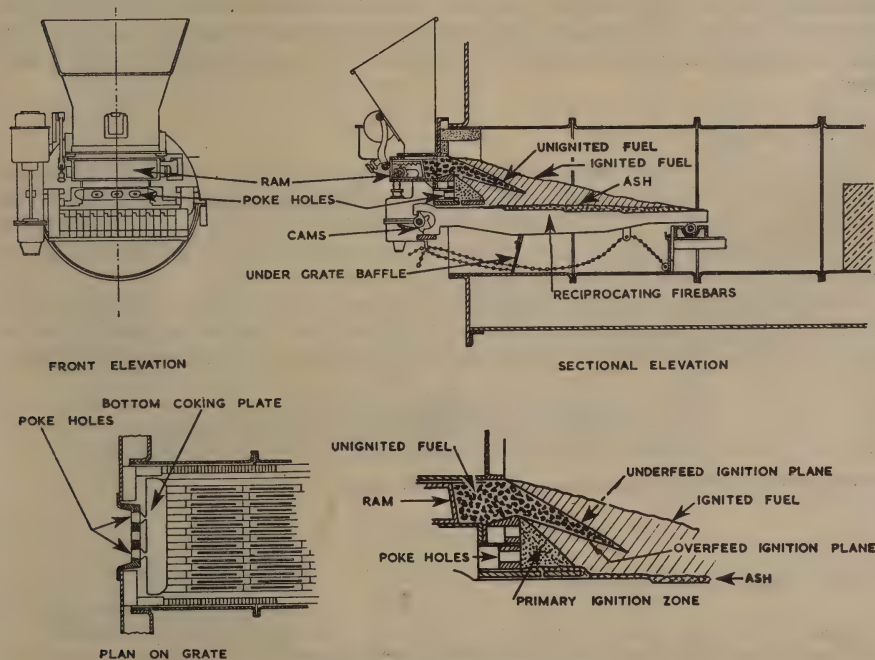


FIG. 4. Ram type coking stoker.

the fuel bed. This action is generally necessary for satisfactory operation of the machine. The firebars are solid, and reciprocate, all moving forward together but odd and even ones returning alternately. Air is drawn, usually by induced or natural draught, up through the firebars and the poke holes, and mixes with the coal. A deflector plate or baffle deflects much of this air into the front part of the fuel bed, air being prevented from entering the ash pit by a cover. Both cover and baffle are lifted for cleaning out the ash pit. The amount of air flowing through the fuel bed is controlled by the boiler dampers.

The amount of coal burned on the stoker is controlled by the speed at which the bars and ram reciprocate, and by the ram stroke. It is generally desirable to operate with a short stroke and high grate speed if the coal has pronounced caking properties.

The coking stoker will handle a wide range of fuels, but is not quite so flexible as the chain-grate type, particularly when operating on fine coal with strong caking properties. Ashpit losses tend to be high with caking coals and much manipulation of the fire is required. In general, however, the firebed should not be disturbed unduly because this tends to cause the emission of smoke and grit.

When firing fine, free-burning coals the amount of unburnt small fuel passing through the fire bars may be excessive, though recent improvements in bar design have helped to reduce this difficulty. With all reciprocating grates, the bar spacing should be as close as possible without causing them to become jammed by pieces of fuel. The makers' advice should be taken on what spacing should be allowed since cast iron bars tend to "grow" on exposure to heat. Any riddlings that pass through the grate should be recovered, wetted, and mixed with the incoming coal returned for burning.

The operator should always watch for coke burning in the ash pit (known colloquially as a "red ash pit"), as has been mentioned when describing the chain-grate stoker. The cause, as indicated previously, may be unduly dry coal, an insufficient supply of air to the stoker, or loss of ignition at the poke-holes.

THE SPRINKLER STOKER

Coal is thrown by sprinkler mechanism, either a rotary-projector or a shovel-projector, more or less evenly over the whole surface of a fixed grate, or on to the front portion of a moving grate arranged and operating similarly to that of the coking stoker. The action of the machine is to throw coal on to the top of the fire, simulating hand-firing by shovel.

The sprinkler type of stoker applied to a reciprocating grate is illustrated in Fig. 5. A spring-loaded shovel flings coal, metered from a hopper by feeder plate to a fire supported on a reciprocating grate similar to that used on coking

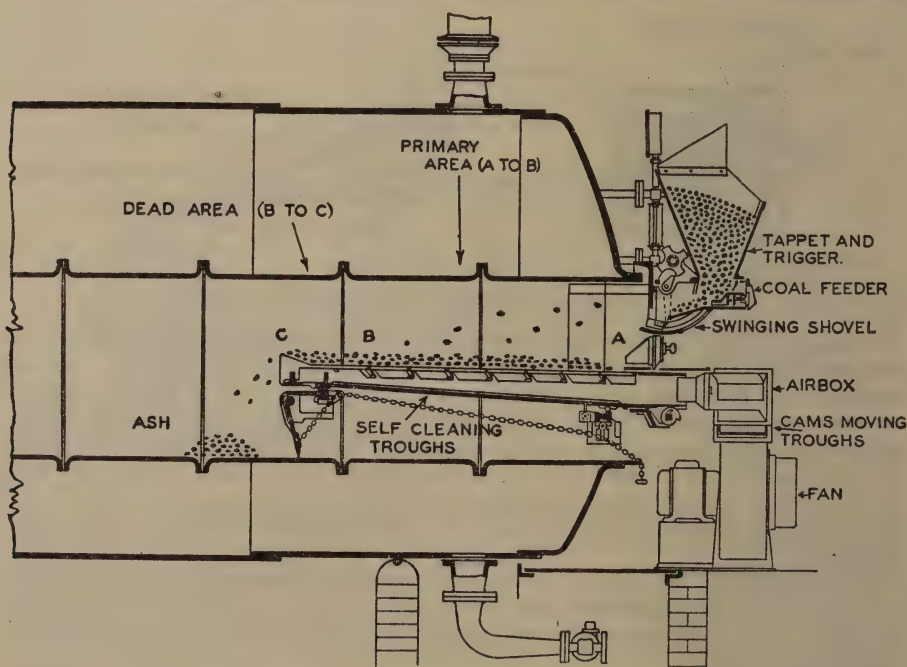


FIG. 5. Moving grate sprinkler stoker, shovel charging.

stokers. Most of the coal is fired on to the front end. If entire coverage were to be attempted by the sprinkling mechanism, some coal would inevitably find its way unburnt into the ash pit.

Air is supplied, usually under pressure, to hollow trough bars, or by induced

or natural draught, to the underside of solid bars. The distribution of coal on the grate can be controlled by altering the tension of the spring or the stroke of the shovel. In some cases a short throw is automatically followed by a longer throw, sometimes as many as five differing throws being available. The rate of coal feed is regulated to suit the steam demand, by the adjustment of the feed plate.

A sprinkler stoker applied to a fixed grate is illustrated in Fig. 6. The coal, supplied from a feeder, is distributed to a rotor. The grate must be cleaned

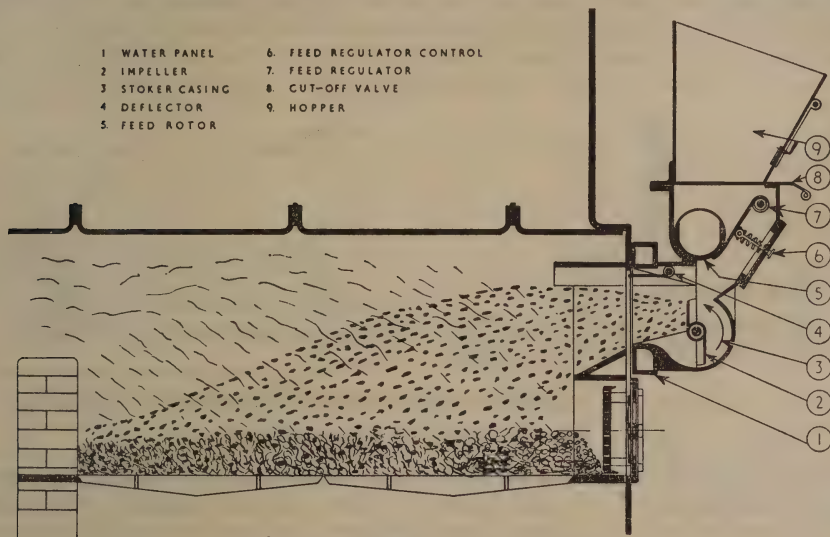


FIG. 6. Rotor type sprinkler stoker.

manually by one of the methods referred to below under Hand Firing.

All sprinkler stokers have three features in common :

- Since they feed coal on to the top of a burning fuel bed, the volatile matter does not pass through an incandescent zone as in chain grate and coking stokers. In consequence, smoke will be produced unless care is exercised in distributing the fuel and in supplying secondary air.
- Particles too large to have sufficient momentum to carry them on to the middle of the grate settle in a mound over the first foot or so of the grate and must be levelled at intervals by firing tools.
- The coal is "air-borne" before it reaches the grate, so that fine particles will be carried over, causing waste and grit nuisance. Fine coals should not, therefore, be used on this type of stoker, particularly for high loads.

THE SPREADER STOKER

This form of stoker, used on water-tube boilers, embodies, at the front of the boiler, sprinkler or spreader mechanism which distributes the coal over a travelling grate working from back to front. The fine particles burn while in suspension, and sufficient combustion volume must be provided for this purpose.

The spreader is of the rotor variety, several rotors being disposed along the front of the boiler. Grit carry-over occurs, the grit being precipitated in an arrestor whence it is re-cycled pneumatically to be burned in the combustion chamber. One of the chief advantages claimed for spreader firing is that it alleviates a major problem sometimes encountered in water-tube boiler opera-

tion, namely, the tendency, particularly with coals of high chlorine content, for deposits to form on the external surfaces of the generator and superheater tubes, and for corrosion to take place in the economiser and air heater. It will also handle a wide range of fuels with great flexibility of operation.

THE RETORT OR "UNDERFEED" STOKER

The underfeed stoker is used extensively for central heating boilers of the sectional type and for vertical steam boilers. It can be used for shell boilers also, especially where the loading is suitable. It is very convenient in form and can be easily arranged to feed coal directly from bunker to boiler. Fig. 7 illustrates such an arrangement. The coal is fed by a worm from the hopper to a cast iron pot or retort in the boiler furnace. Air is supplied to the pot

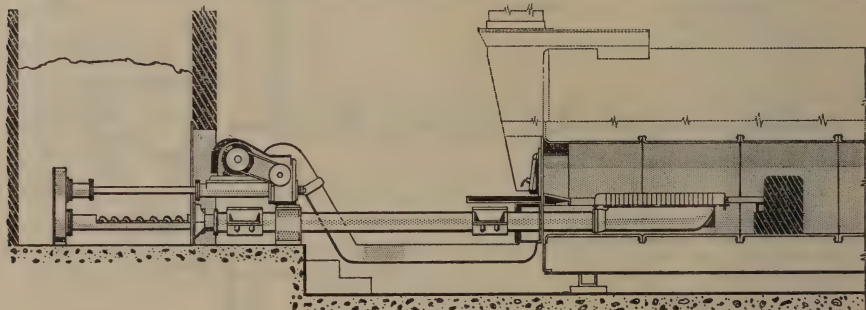


FIG. 7. Underfeed stoker, bunker-to-boiler firing.

through a separate tube and issues through ports or tuyères cast in the upper part of the pot. Coal is forced upwards in the pot and is partly penetrated by air from the tuyères. Combustion is initiated and maintained in the upper part of the pot, whence burning coal spills over on to grates surrounding the pot, where combustion is completed. The grates are cleaned manually at suitable intervals.

This type of stoker may suffer from the fact that the penetration of air into the coal in the retort is imperfect, a central core of coal rising unmixed with air. This may cause the formation of a black core of partly coked coal, with risk of smoke emission. With strongly caking coals this black core may create difficulties. It may extend into "trees", which will have to be broken down manually. Excessive fines in the coal may also create difficulty, since they segregate to the bottom of the feed, and then rise in the retort at the end remote from the entry of the feed screw. If this happens, since fine dry coal is resistant to air flow, the rear end of the fire will tend to become dead. Underfeed stokers should, therefore, be supplied with graded coal. One maker claims to have overcome the difficulty by dividing the core into two by means of a central casting provided with tuyères.

The underfeed stoker is also used in high temperature furnaces and kilns where, owing to the presence of very hot brickwork, trouble from smoke caused by the black core is greatly reduced.

FEED RATE CONTROL WITH MECHANICAL FIRING APPLIANCES

With all types of moving grate the rate of travel of coal is controlled by varying the speed of the sprocket shaft (in the case of the chain grate) or of the camshaft (in the case of coking stokers and sprinklers fitted with self-cleaning grates). Speed control is achieved by several methods, most of which can be incorporated in automatic control systems operating from boiler pressure, steam flow, temperature or time.

Variable speed D.C. electric drives are often used as well as adjustable ratchets. One "miniature" variety of chain grate designed for central heating boilers uses a silent ratchet.

Another make of chain grate uses an interrupted electrical supply, the time "ON" being adjustable relatively to the time "OFF". This type of control is relatively cheap and appears to be quite satisfactory. A.C. variable-speed drive is also used. These methods would appear to have advantages over the older device of three-speed pulleys in that change of speed is accomplished more conveniently over a wider and more continuous range. They are also more easily adaptable to automatic control.

COAL FOR MECHANICAL STOKERS

The size and kind of coal that can be burned satisfactorily on mechanical stokers may be summarised as follows:

(1) Fuel must be small enough to pass through the openings at the hopper bottom, at the feed gate, under the guillotine or through any fuel-regulating device. The upper size limit is about 2 in. but sizes smaller than this are generally much more desirable for both convenient handling and efficient combustion.

(2) Fuel must not be so small as to be blown off the grate or pass through the air slots in the grate.

(3) Too low an ash content may cause overheating of the grate, too high an ash content (say over 20 per cent.) can cause much waste in the form of unburnt fuel in the ash pit and may necessitate excessive manipulation of the fire, especially if the ash is easily fusible and if the coal contains much fine material. This will certainly result in lower boiler efficiency and perhaps reduced output.

It is not possible to prescribe any general rule regarding the ash content of coals for boiler firing, since the design and method of operation of individual boiler plants vary widely. The safe principle to apply is that coal used for steam raising should contain sufficient ash to protect the firebars; the ash content should not be below about 7 per cent.

Table 1, embodying the recommendations of the Combustion Engineering Association and quoted by Matthews¹, may be taken as a useful guide. In this table the dividing line between large and small boilers is 60,000 lb. of steam per hour.

TABLE 1
METHOD OF FIRING IN RELATION TO ASH CONTENT OF COAL

Type of Boiler	Method of firing	Draught	Size	Maximum permissible ash content of coal per cent
Water-tube	Chain-grate	Forced	Large	25
do	do	do	Small	20
do	do	Natural	Large	20
do	do	do	Small	15
Shell ..	Mechanical (except underfeed)	Forced		15
		Natural		10
do	Mechanical (underfeed) ..			10
do	Hand-fired			10
do	Certain special cases			6

(4) Most bituminous coals, in particular Groups 600 to 900, can be burned on any stoker. Metallurgical coking coals (N.C.B. Nos. 300-500) should be avoided in the interests of conservation for the carbonization industry requirements. Anthracite, particularly if fine, is not really suitable; it cannot be burned on retort or underfeed stokers.

For further information as to the suitability of various coals for use on the different types of stoker, reference should be made to the following two publications of the Combustion Engineering Association:

"Firing Equipment and their Fuels."

Section I. Shell Boilers Fired by Solid Fuel.

Section II. Water-tube Boilers Fired by Solid Fuel.

(5) If coal containing much fine material has to be used, it should be carefully conditioned by wetting. With no wetting the coarse and fine particles tend to segregate giving alternately permeable and dense patches. Conditioning by wetting evens out the fuel bed resistance and thus also the rate of air flow. The gain in efficiency from wetting small coal is important, as may be seen from Table 2. This question is discussed in more detail in Chapter 8.

TABLE 2
EFFECT OF MOISTURE ON FINE COAL ($\frac{1}{8}$ IN.—0)
IN RELATION TO BOILER EFFICIENCY*
Ash content of coal—about 10 per cent.

<i>Moisture level</i>	<i>Free moisture : per cent</i>	<i>Efficiency : per cent</i>	<i>Evaporation : lb./hr. f. and a. 212° F.</i>
High	19.8	66	6,700
Medium high	$\left\{ \begin{array}{l} 11.0 \\ 10.2 \\ 10.2 \\ 11.5 \end{array} \right.$	$\left\{ \begin{array}{l} 73 \\ 72 \\ 74 \\ 74 \end{array} \right.$	$\left\{ \begin{array}{l} 7,200 \\ 7,200 \\ 7,300 \\ 7,000 \end{array} \right.$
Average ..	10.7	73	7,200
Medium low	$\left\{ \begin{array}{l} 8.4 \\ 7.3 \\ 7.1 \end{array} \right.$	$\left\{ \begin{array}{l} 70 \\ 72 \\ 71 \end{array} \right.$	$\left\{ \begin{array}{l} 7,000 \\ 7,200 \\ 7,300 \end{array} \right.$
Average ..	7.6	71	7,200
Low	$\left\{ \begin{array}{l} 1.3 \\ 0.9 \\ 0.8 \\ 0.9 \end{array} \right.$	$\left\{ \begin{array}{l} 56 \\ 63 \\ 51 \\ 46 \end{array} \right.$	$\left\{ \begin{array}{l} 4,300 \\ 4,900 \\ 4,400 \\ 3,750 \end{array} \right.$
Average ..	1.0	54	4,340 = 60 per cent. M.C.R.

The inherent moisture of the coal was slightly under 1 per cent.

*With acknowledgment to B.C.U.R.A. The work was carried out on a chain-grate stoker fitted to an Economic boiler.

Coal should be wetted so as to contain up to $1\frac{1}{2}$ per cent. of free moisture for every 10 per cent. of coal passing through an $\frac{1}{8}$ -inch screen. This is in keeping with the well-known "ball test", in which coal when squeezed in the hand just coheres as a ball without exuding moisture. For information on the subject see Fuel Efficiency Bulletin, No. 53².

HAND FIRING

There is no sound justification for retaining hand firing except in the smaller installations where mechanical stoking cannot be justified on economic grounds. The general emphasis on smoke-free operation of coal-burning plant is bound to render hand firing obsolete in a comparatively short time. The principles and practice of hand firing are described in "The Stokers' Manual" (H.M. Stationery Office). Nevertheless some of the principles involved are dealt with below.

The Principles of Firing. Since the object is to burn the fuel completely with the smallest quantity of excess air, the first step in boiler management is good maintenance. The technique of preventing air inleakage has been emphasised earlier in this chapter.

When it is established that substantially all the combustion air is entering the system through the boiler furnace, the next step is to secure proper contact between the air and the fuel. Combustion can be regarded as a dual operation in which the fuel "burns" the air and the air burns the fuel. Just as it is important to avoid unburnt fuel passing in substantial amounts into the clinker and ashes, so too it is important to avoid more oxygen than is absolutely necessary, as has been indicated earlier in this chapter, passing "unburnt" to the chimney. For these conditions to be secured it is necessary that the fuel bed be free from holes and bare patches, and that the gases above the fire-bed contain sufficient air to burn them completely and be in a state of sufficient turbulence to obtain good mixing. Because the mixing of air and combustible gases from the coal is imperfect, it is necessary in practice to admit some excess of air over that theoretically required. *Failure to secure complete combustion of the volatiles is the one and only cause of dark smoke emission.*

The amount of air required in a well-managed boiler will depend entirely on the rate at which the coal must be burnt to maintain the required output of steam. The total amount of air passing through the boiler furnace is controlled by operating the dampers. Dampers should be adjusted according to the load, and the secondary air required to burn the volatile matter above the firebed should be admitted as required through the overfire air grids. To burn more coal, more air must pass through the grate; to burn smoke there must be more free oxygen above the firebed. The management of the air admission is a skilled task, success of which can be deduced either from the indications of the CO₂ recorder or (when burning bituminous coal) by the maintenance of a slight haze from the chimney.

With very thin fire-beds, such as are generally used with sprinkler stokers, the over-fire air is derived from that which passes unburnt through the firebed. Under such conditions little or no secondary air need be admitted above the firebed through the air grids and fire-doors. The appearance of the chimney outlet will serve, as previously indicated, as a good practical guide to the distribution of air. *Arrangements should therefore be made so that the top of the chimney can be seen from the firing floor.* Better still, a smoke density meter should be fitted. *The damper controls should be situated on the firing floor in a position easy of access by the fireman as he inspects the furnace.*

Since the quantity of coal burnt in an efficient boiler will be directly proportional to the amount of steam produced, there is need to adjust the rate of coal feed from time to time. The faster rates of combustion will in general require a thicker fuel bed to prevent the formation of holes or bare patches through which the air can pass unburnt. The size and nature of the coal also affect the firebed thickness; the larger the size of the fuel, the thicker the bed. For every coal there is an appropriate thickness of fuel bed which the fireman

must discover by experiment; by the aid of a draught gauge connected to the furnace, the fireman can discover by trial the best draught and firebed thickness to give a good CO_2 content of the waste gas corresponding to the load on the boiler.

Thin firebeds, of the order of 2 in. to 4 in., answer more quickly to variations in load than thicker fires, but demand greater care and must be maintained in very good condition, as otherwise they soon burn out. With such beds the draught should be as low as possible consistent with producing the necessary steam. If the CO_2 of the outlet flue gases is low, it is an indication either that too much draught is being used or that the fuel bed is uneven.

The importance of avoiding bare patches has been emphasised. Bars too thinly covered at the back will allow cold air to pass through unused while if the fuel bed is too thick at the back, live coal only partly burnt will be carried over with the ashes. The cure when the end of the grate becomes uncovered is to increase the coal feed or reduce the draught, according to whether more or less steam is required; the cure for excessive carbon carried over the back into the ashes is the reverse. Nor must it be forgotten that the primary air admitted beneath the firebars keeps them from becoming overheated. If the bars are found to become red-hot, a probable cause is some factor that prevents sufficient air from passing through them to keep them cool such as insufficient draught or the formation of clinker.

The dimensions of the grate should be appropriate to the maximum load on the boiler. Although a mechanical stoker unit will be designed initially to suit the load, grate dimensions must be taken into account should the load change permanently. In hand firing, where a grate is too large, economies have resulted from shortening the grate by building up the end near the bridge with refractory bricks, as a temporary measure, and by removing sections of the grate as a more permanent alteration. If sections of the grate are removed, the bridge wall must be moved to correspond with the new grate length.

Hand Firing with Slurry and other Low Grade Fuels. The term *low-grade* may be considered to refer to such products as belt pickings, middlings, duff, fines and slurry, generally of high ash content, exceptionally fine in grain size, often very wet and almost always of very low calorific value.

The behaviour of low-grade fuels varies very much in different types of grates and furnaces, but generally the best results will be obtained only with furnaces of the forced draught type. Low-grade coals can sometimes be blended with others of better quality, but special blending equipment will be necessary to achieve this.

With duffs, fines and slurries the fires must be raked at frequent intervals in order to keep the fuel bed open and to prevent the fires from dying down. With inferior slurries or filter cake the firebed should be of good depth, say 10–12 in., to give the necessary “body” of heat to ignite the fresh fuel as added. High under-grate air pressure is necessary; not less than 3–4 in. w.g. should be available

BURNING RATE

The rate at which coal can be burned on a grate depends on the nature and size of the coal and on the rate of air supply to it, as well as on the distribution of air through the gate. For industrial boilers the burning rate at present normally varies between 10 lb. and 40 lb./sq. ft./hr. The present (1957) customary limitation in designing hand-fired grates and mechanical stokers to a maximum of about 40 lb./sq. ft./hr. is largely a matter of tradition and this present upper limit will probably be increased as research discovers more about

the limiting factors. Rates of 100 lb./sq. ft./hr. and more have been achieved, for example in locomotives.

The air supply must be adjusted by manipulating the air controls to the burning rate required. Unless adequate draught is provided it will be impossible to draw in sufficient air to burn the required maximum quantity of fuel. The precise amount of draught (see Chapter 8) required for a given rate of combustion will depend on the resistance through the fire-bed and flues. Assuming that the boiler flues are clean enough to offer no abnormal resistance, the controlling factor is the resistance of the fuel bed. This in turn will depend on the size of the coal, its moisture content, its caking properties and the thickness of the bed. With every class of coal there is some thickness of fire that will fit in best with existing conditions. To accommodate continuous firing at loads well below the designed capacity, the grate may with advantage be shortened; this, in particular, assists in reducing bare patches. The approximate natural or induced draught required over the fire is related to the burning rate, when hand-firing on slack as follows:

Max. burning rate, lb./sq. ft./hr.	..	..	..	15	20	25
Draught, inches w.g.	..	..	..	0.15	0.20	0.30

It is important to avoid grit emission so far as is practicable. Grit emission is dependent on burning rate but more on the size grading of the coal, on its moisture content and on the distribution of the air through the fuel. The finer particles tend to be carried away in the gas stream and even if they are largely burnt during their passage over the fire, they contribute to the fly-ash and grit emission. Attention to fuel conditioning by wetting (Chapter 8) helps to prevent the finer particles from becoming air-borne. The local air velocity through the fuel-bed has an important influence on the emission of fly-ash and grit. The occurrence of a blow-hole will greatly increase the air velocity; the effect obviously depends on the size of the blow-hole. The presence of patches of clinker causes higher air velocity elsewhere. A high air velocity at the back of a mechanical stoker, where the residual carbon is being burnt off, encourages grit and dust emission. It is possible with the same coal to have variations between 1 and 100 in the relative amounts of grit and dust emission according to the conditions.

The limitations of burning rate because of possible grit emission are largely independent of the method of firing, except in the sprinkler or spreader method where fine coal is burnt in suspension and the ash is carried away before it can reach the grate. Plant fired by this method in populous areas will require grit arrestors to reduce air pollution.

There are wide variations in burning rate over the whole area of the grate. When there is an adequate depth of coal in the zone of active combustion the burning rate may even be twice as great as that for the design figure, e.g. 35-40 lb.; whereas at the back of a mechanical stoker where the coal has been largely burnt to ash the rate of combustion is very much lower. It is probable that improved technical practice over the next few years, mainly in attention to the factors here referred to, will result in much higher burning rates than have hitherto been used. British Coal Utilisation Research Association workers have designed a short chain grate which, by achieving better distribution of the air, is claimed to give an average burning rate of 80 lb./sq. ft./hr. without involving an increase in grit emission or other ill effects.

Under-grate air control is available on water-tube boilers, enabling the amount of air supplied to different parts of the grate to be adjusted. For example, the primary air supply to the burning-off zone at the back of the grate is reduced and more air is supplied in zones of intense combustion. On some boilers the average rate of combustion for a given class of coal is substantially increased.

The method of quoting rates of combustion in lb./sq. ft./hr. is misleading because it ignores differences in calorific value and in ash content of the coal. A sounder and more satisfactory method of expression would be to indicate burning rate in terms of heat release—B.t.u./sq. ft./hr.

SMOKE ELIMINATOR DOORS

From what has been said on the subject of hand-firing it will be evident that it is difficult, with bituminous coals, to prevent smoke emission. To meet this difficulty devices were developed during the 1939–1945 war at the Fuel Research Station for natural draught and forced draught firing on ships.

Since the War these designs were modified for land boilers. For natural draught the Fuel Research Station smoke eliminator door, illustrated in Fig. 8, was developed. In this door a “continuous” air supply passes into the furnace through two large streamline nozzles. A “supplementary” air supply, i.e. extra air required after firing, to burn the ‘volatiles’ in the fuel, is admitted through a box formed on the inside of the furnace door. The air enters the box near its base through a large rectangular opening, and leaves it through an annular space around the nozzles and through a number of holes drilled

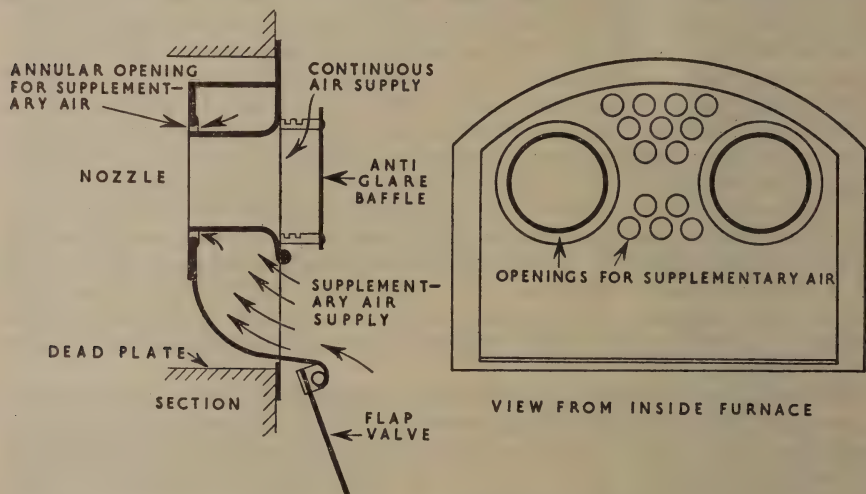


Fig. 8. F.R.S. smoke eliminator door.

in the face of the box. The supplementary air entering the box is controlled by means of a flap valve hinged in such a way that it opens automatically when the fire door is opened. The valve is closed by hand when the evolution of volatile matter has abated.

The fire door has been developed to suit the requirements of hand-fired land boilers. It consists of a modified fire door provided with ports admitting controlled and directed secondary air.

These doors can be made up in any reasonably-equipped workshop. They do not *automatically* prevent the production of smoke, but require intelligent operation by the fireman.

For forced draught installations the Fuel Research Station has recently designed a forced draught smoke eliminator, shown in Fig. 9. In this case the secondary air is supplied through two nozzles fitted above the fire door. Three dampers are incorporated in the device. The butterfly damper is operated automatically when the fire door is opened or closed, thus shutting off the

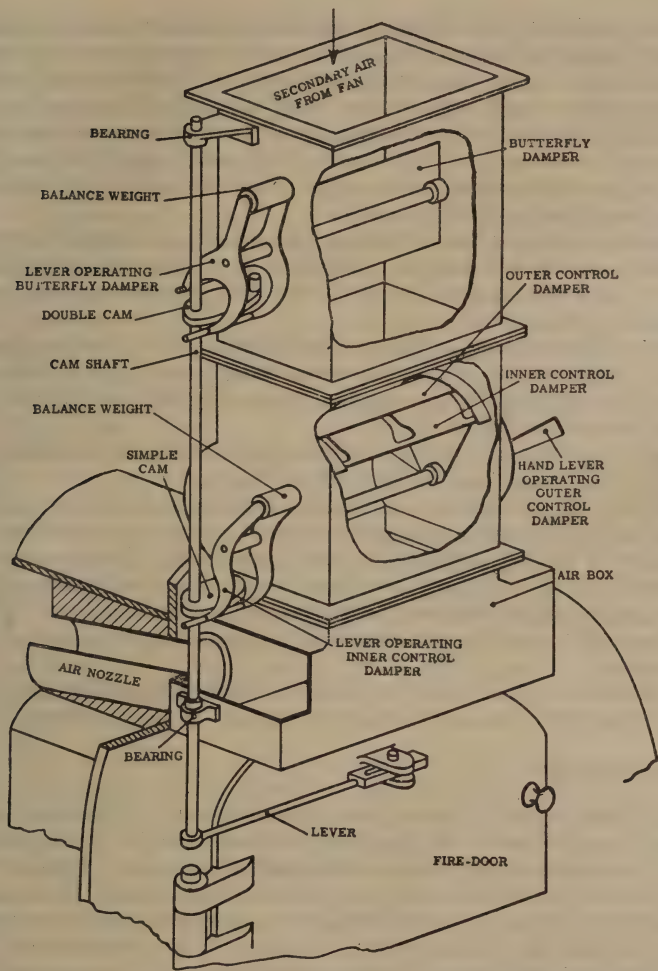


FIG. 9. Fuel Research Station smoke eliminator for shell boilers with forced draught.

secondary air supply when the door is opened and preventing any blow back. The outer damper controls the maximum quantity of secondary air admitted to the furnace and is operated by hand when the boiler load changes. The inner damper is semi-automatic in operation, being moved mechanically into the open position when the fire door is opened but closed by hand when it is seen that the evolution of 'volatiles' has virtually ceased.

CLINKER FORMATION

Clinker consists of a matrix of fused ash in which may be embedded particles of partly burned fuel. By its nature it impedes flow of air to the fuel bed and so must be removed. With mechanical grates, clinker may adhere to the side bars or to the refractory parts where these touch the fuel bed; in either case it impedes the free flow of coal along the grate and results in an uneven fuel bed and inefficient combustion. Its removal necessitates the use of the slice.

More clinker trouble is experienced with some fuels than with others, and whilst it is difficult to forecast from the analysis of a coal whether or not clinker will form, the following points should be noted:

- (i) Coals with low ash fusion temperatures will generally clinker more readily than those with high ash fusion temperatures, but ash fusion temperatures are only a rough guide to the tendency to form clinker.
- (ii) Coals with a wide ash fusion range (i.e. the difference between the "initial deformation" and the "blob" temperatures) cause difficulty.
- (iii) Coals of low reactivity (generally high rank coals) because they burn at high temperatures, may cause more difficulty, even when the ash fusion properties are moderate.
- (iv) Clinker formation takes time, and hence ash, if allowed to remain long enough in the fire may form clinker. A mechanical grate which positively and continuously removes the ash, possesses an obvious advantage in this respect.
- (v) Manual disturbance of the fuel bed results in the development of high local temperature, which promotes clinker formation. It also tends to mix up ash with the burning fuel, where the high temperature induces the formation of clinker.
- (vi) Once it is formed, clinker attaches itself, because it is sticky, to more ash, which fuses and enlarges the clinker.
- (vii) Clinker will adhere to a hot surface rather than to a relatively cold one and to a rough surface rather than a smooth one. Overheating of grates or side seals should be investigated and the cause removed.
- (viii) Small coal will, if properly wetted, burn more readily than large coal, but may tend to become embedded and lost in fused ash. Small coal, a low ash fusion temperature and a high ash content are a bad combination.

A full treatment of the subject of clinkering will be found among the papers presented at the 1953 Ash and Clinker Conference of the Institute of Fuel.³

GAS SIDE DEPOSITS

Slagging is the cause of water-tube boilers having to be closed down for cleaning and maintenance at frequent intervals, with consequent loss of capacity. The trouble is not unknown in multitubular shell boilers.

Deposits may occur either at high or at low temperatures. The most serious high temperature deposits occur mainly on superheater surfaces and consist of fly-ash particles bonded together by a matrix of sulphates of the alkali metals, sodium and potassium. Another similar type of deposit consists of fly-ash particles bonded by acid phosphates. In the hottest part of the boiler a third type is found in which the fly-ash particles are hardened as the result of fusion or sintering, and here there is usually found an inner layer of alkali sulphate by which the deposit is attached to the tubes. This type of deposit is often found in pulverized-fuel-fired boilers.

Two types of deposits occur on surfaces at lower temperatures. On economisers hard masses may collect consisting of sulphates and phosphates of iron, calcium and aluminium; when these contain more than 10 per cent. of phosphate they prove very difficult to remove. On air heaters, there may be found accumulations consisting of a mixture of flue dust, sulphuric acid and the products of acidic corrosion of the underlying metal.

The cause of these deposits is the sulphur and alkali chloride contained in the coal, with phosphate playing a significant though probably secondary part. Sulphur is found in flue gases mainly as sulphur dioxide; but small amounts of the dioxide are converted into the trioxide—the anhydride of sulphuric acid. It has been found that small amounts of SO_3 raise the dew point of the flue gas, and consequently enable acid liquor to be deposited on surfaces at temperatures as high as 250 to 300° F., with consequent corrosion.

Sodium and potassium chlorides are volatile at the temperature of the fire-bed and during passage through the flues may be converted into sulphates by interaction with the SO_3 that may be present in small amounts; at temperatures at which the chlorides would be still in the vapour phase, the sticky sulphates thus formed adhere to surfaces on which the fly-ash is trapped and further deposit is thus built up.

A secondary element of interest in this problem is boron. It has been established that both boron and phosphorus are volatilised from stoker-fired boilers, particularly with thick fuel beds and under reducing conditions, and boron phosphate may be formed; this is an important constituent of hard economiser deposits.

There is abundant evidence that the formation of deposits can be affected by the conditions in the fuel bed and furnace, though this may be due to the influence of the conditions on the boiler heating surface rather than to the manner in which the fuel is burnt. Attempts are being made to absorb or neutralise the sulphur trioxide by introducing dust. This may be carbon smoke (for example, a little soot formation may be allowed), zinc oxide smoke, or pulverized fuel precipitator dust; it has been found that additions of 0.25 per cent. zinc oxide or 6 per cent. of precipitator dust by weight of fuel burned are sufficient to cause a very material reduction in the dew point and in the quantity of alkali sulphates formed in the flue gases.

This subject has been under investigation for some years by the Boiler Availability Committee, who have concluded that in the present state of knowledge it cannot be too strongly emphasised that thorough cleaning of all surfaces when the boiler is shut down is the most effective method of retarding the rate of growth of deposits.⁴

GRIT EMISSION

It is becoming essential to avoid the emission of grit and dust from industrial plant, including boilers, in addition to ensuring that there shall be no emission of dark smoke. A distinction must be drawn between grit and dust. The larger sizes of particles discharged through the chimney into the air are sufficiently large to fall to the ground easily and within a few yards of the chimney. Such particles would be termed grit. Particles greater than 200 B.S. sieve size (0.076 mm.) are distinctly gritty and would cause eye irritation but they may be carried some distance from the chimney by a prevailing wind. The borderline between dust and grit may be regarded as somewhere in the region of this size. On the other hand, particles having a size equivalent, in free-falling speed, to ash particles less than 20 microns in diameter, are so fine that they remain suspended almost indefinitely in natural air currents.

Mechanical mining is producing a much greater proportion of the coal in the smaller sizes and a higher proportion of fine particles. The smaller sizes of coal, say below $\frac{1}{8}$ in. are liable to give off ash and grit particles which are carried through the boiler and out of the chimney stack. The greater the velocity of gases through the boiler furnace the more grit will the flue gases tend to carry away; with forced draught used commonly for burning low-grade small coals more dust and grit are carried away than with natural draught when burning larger coal.

The emission of grit and dust may be reduced materially (1) by keeping the amount of excess air to the minimum and so reducing the velocity of the gases, through the boiler, (2) by correct wetting of the fuel before combustion, (3) by installing a grit arrestor between the boiler and the chimney. The nuisance may be abated by raising the height of the chimney.

The type of fuel, moreover, influences the emission of grit and dust apart from its size. Fuels that tend to coke, particularly if adequately wetted before

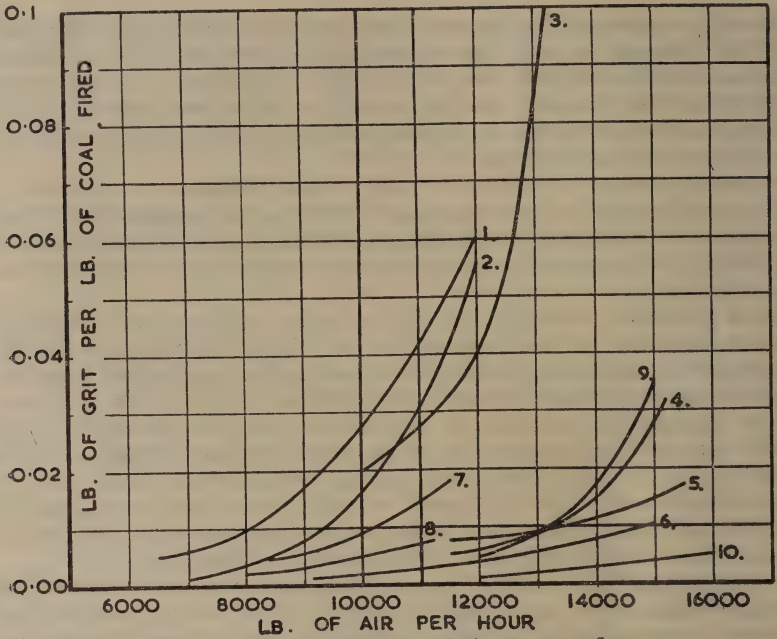


FIG. 10. Grit carry-over in relation to mass flow.

- Curve 1. $\frac{1}{2}$ in.-0. Free burning coal, dry and slagging.
" 2. $\frac{1}{8}$ in.-0 " " " " "
" 3. $\frac{1}{8}$ in.-0. Coking coal " " " "
" 4. $\frac{1}{2}$ in.-0 Free burning coal, no slagging.
" 5. $\frac{1}{8}$ in.-0. Coking coal, "
" 6. $\frac{1}{2}$ in.- $\frac{1}{8}$ in. Free burning coal, "
" 7. Pelleted slurry, 30 per cent. ash frequent ashpit cleaning.
" 8. $\frac{1}{2}$ in.-0 Free burning coal, high ash content.
" 9. $\frac{1}{2}$ in.-0. Coking coal, slagging.
" 10. $\frac{1}{2}$ in.-0. Coking coal, no slagging.

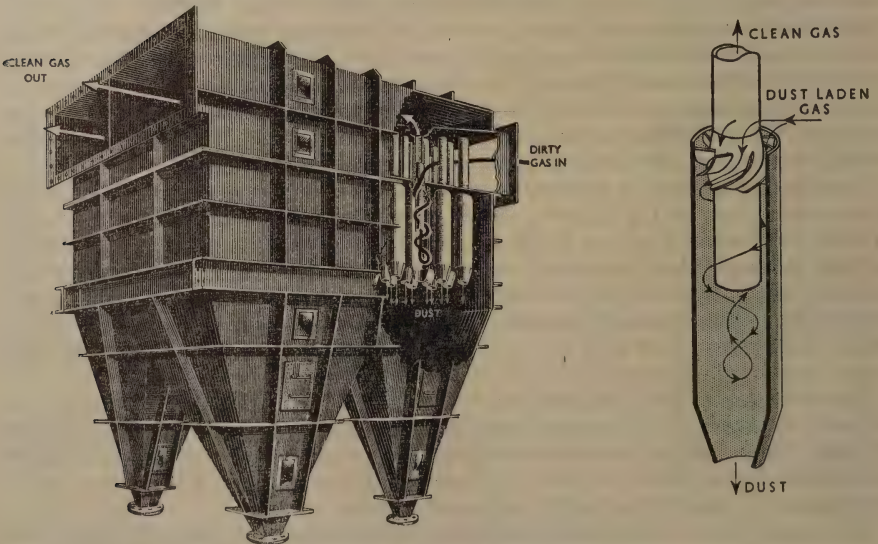


Fig. 11. Multi-cell grit arrestor.

firing, will not be such great offenders as the fuels which contain little or no caking properties, e.g. anthracite duff. In illustration of these general statements, Fig. 10 shows the relationship which exists between grit carry-over and gas flow through the boiler.

Grit carry-over also varies according to the firing method. The grit and dust concentration in the flue gases from a fully loaded boiler fired with pulverized fuel may be as high as 6.0 grains per cubic foot of gas at N.T.P. Normally the dust concentration from a boiler equipped with a mechanical stoker should not be more than 0.3 grains per cubic foot of flue gas. Thus with pulverized fuel firing the most efficient (albeit costly) dust extraction plant is necessary if the dust concentration of the gases leaving the chimney is not to exceed the recommended maximum of 0.4 grain per cubic foot at N.T.P.⁵

The Clean Air Act, 1956, prescribes penalties for failing to take adequate steps for "minimising the emission of grit and dust" from boiler furnaces and ovens and metallurgical plant. [Sec. 5 (1)]. On large installations electrostatic precipitators are commonly used but grit arrestors consisting of a large number of small cyclones have been developed to compete in this field. The grit arrestor shown in Fig. 11 is an example of this type.

Dust extraction plant may not be necessary where mechanical stokers are employed but even if the boilers are heavily loaded or the coal is very free burning with a high percentage of fines a cyclone type arrestor will be able to reduce the grit emission to a satisfactory level. Most industrial boiler plant grit arrestors are of the single cyclone type installed in the main flue before the stack, though a number of smaller cyclones may be arranged in parallel and one or more used according to boiler load. This tends to give more efficient dust extraction on variable load than a single cyclone.

Fig. 12 shows another type of grit arrestor in the form of a grit-arresting induced draft fan. The grit-arresting fan usually takes less space than the cyclone and separate fan but absorbs more power.

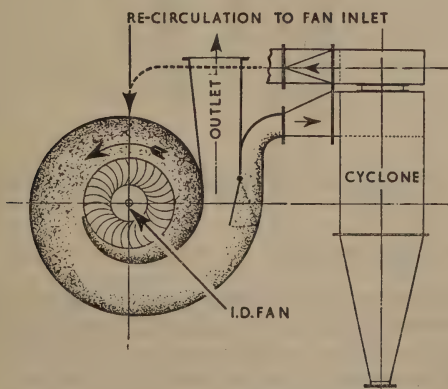


FIG. 12. Grit-arresting induced draught fan.

Fig. 13 illustrates a type of single-unit cyclone that can be mounted at the top of the stack. This has recently been developed as a low cost arrestor for the smaller boiler plant. Most grit arrestors will remove a high percentage of the grit entering them but do not effectively remove dust.

Methods of measuring grit and dust emission are described in British Standard 893.⁶

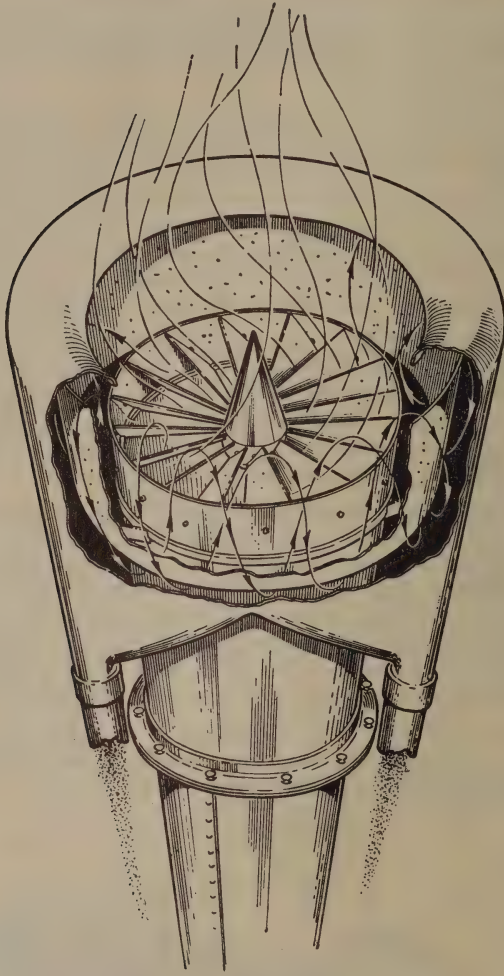


FIG. 13. Single unit grit arrestor for stack mounting.

CLEANING HEATING SURFACES

Dust on the heating surfaces of boilers impedes heat transfer. It has been shown that dust accumulating in the flues of a Lancashire boiler over a period of 50 days can cause a loss of boiler efficiency of the order of 7 to 8 per cent.; in some quarters this is regarded as an under-statement.

One device that can be used effectively to prevent the accumulation of dust in the furnace tube is the inverted bridge wall or "baffle". Fig 14 shows the arrangement which consists of a refractory baffle obstructing the top half of the furnace tube, placed about one furnace tube diameter downstream from the bridge wall. This simple device, which can be either home-made or purchased from manufacturers, causes the gases to move along the bottom of the furnace tubes, rather than along the top, as would otherwise be the case. This action causes the dust to be swept forward, and in this way the furnace tube heating surface is kept clean.

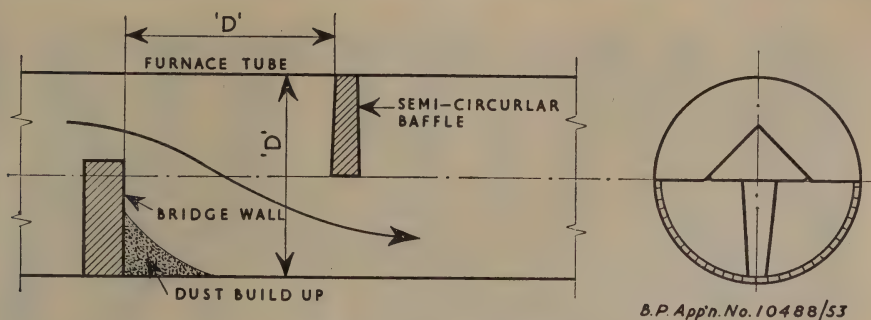


FIG. 14. Furnace tube baffle.

B.P. App'n. No. 10488/53

The daily use of soot-blowers will remove dust and restore efficiency. If allowed to persist over a long period dust accumulation may also reduce the draught available in the furnace. Fig. 15 shows an arrangement of soot-blowers in Lancashire boilers, incorporating a system of vacuum removers. Another system used with multitubular boilers consists of a violently pulsating blast of compressed air or steam; this is most effective in cleaning smoke tubes. This device, known as a "percussion lance", is shown in Fig. 16. A multitubular boiler can be cleaned by this device in a fraction of the time needed when using brushes and with much less effort. Even so, the removal of deposits is just as effective except in those cases when the deposits are hard, sintered or bonded. The use of furnace tube blowers is specially important in the operation of Economic boilers, where the accumulation of grit behind the bridge can lead to dangerously high combustion chamber temperature in a hard-worked boiler. Steam soot blowers, particularly of the type arranged to blow each tube from the smoke box end (Fig. 17), are also effective when used regularly.

Whenever boilers are cleaned by blowing there is likely to be heavy grit emission from the stack during the operation. This is catered for by installing collecting equipment capable of adjustment during these periods of heavy dust concentration, and of giving their stated collective efficiency whatever may be the concentration of dust in the gases.

WATER LEVEL

When steam is released from the surface of water in a boiler, foam may be present to a depth of perhaps several inches. The nearer the top of this foam layer is to the steam off-take from the boiler, the more likely it is to be entrained by and carried over the steam. This is particularly likely to occur if the dissolved solids, suspended solids or alkalinity, or all three, are high (see Chapter 16, "Boiler Feed Water Treatment", page 384). The higher the water level the more likely is carry-over to occur.

Whilst a certain amount of blowing down is essential, if it is excessive or if the blow-down valves leak, avoidable heat losses occur. The amount of water rejected should therefore be carefully controlled and reduced to the minimum necessary to maintain the boiler water sufficiently free from impurities.

The pipes leading from the blow-down valve should be examined to see that no leakage is occurring when the valves are closed. A general indication that the boiler should be blown down is surging of the water in the gauge glass.

To avoid priming, the total dissolved solids should be kept as low as possible, and the amount of blow-down will, therefore, depend on this, on the rate of

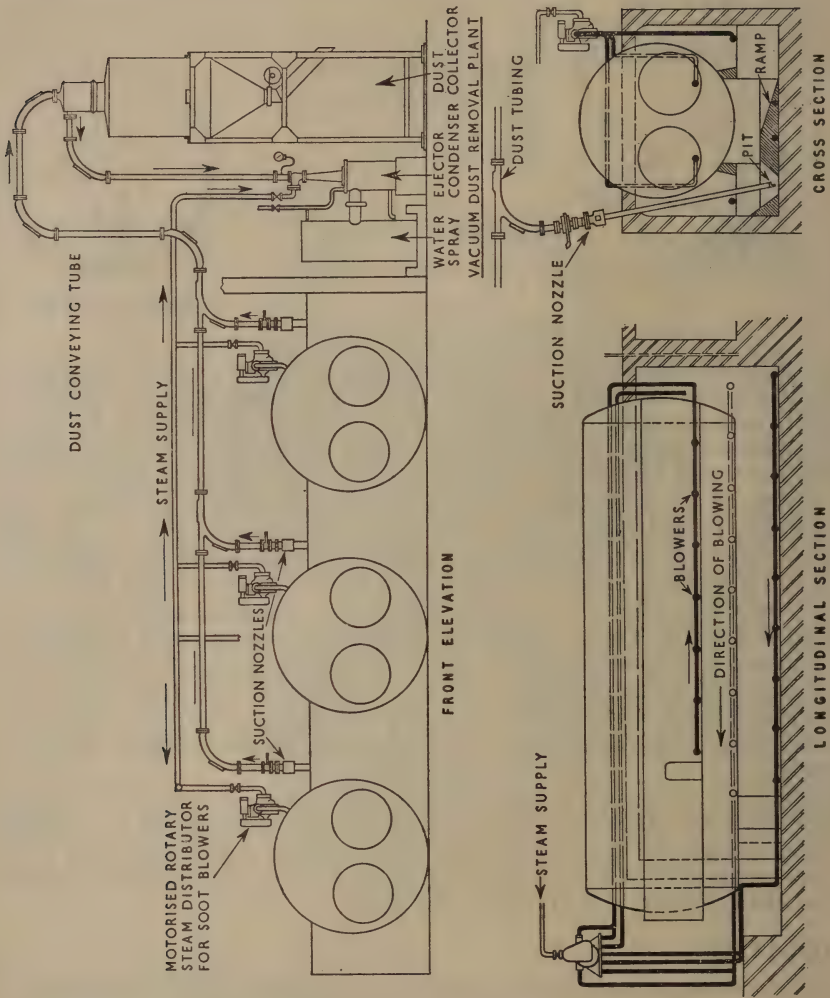


Fig. 15. Arrangement for soot blowing in Lancashire boilers.

steaming and on the composition of the feed water (including any returned condensate), and on the maximum T.D.S. that can be tolerated without risk of priming (see Chapter 16).

The quantity of boiler blow-down required can be calculated as follows:

Let x be the gallons of make up added per day, a , the total dissolved solids (T.D.S.) in grains per gallon in the feed water, y , the gallons of water blown down per day, and b , the T.D.S. in this blow-down.

Since to maintain the solids in solution at a predetermined level the amount of dissolved solids removed from the boiler at blow-down must equal the amount of dissolved solid added per day in the feed water,

$$ax = by, \text{ whence } y = \frac{ax}{b}$$

Blow-down represents a waste of heat; this may be worth recovery by one of the methods suggested in Chapter 21, where the whole subject is dealt with more fully.

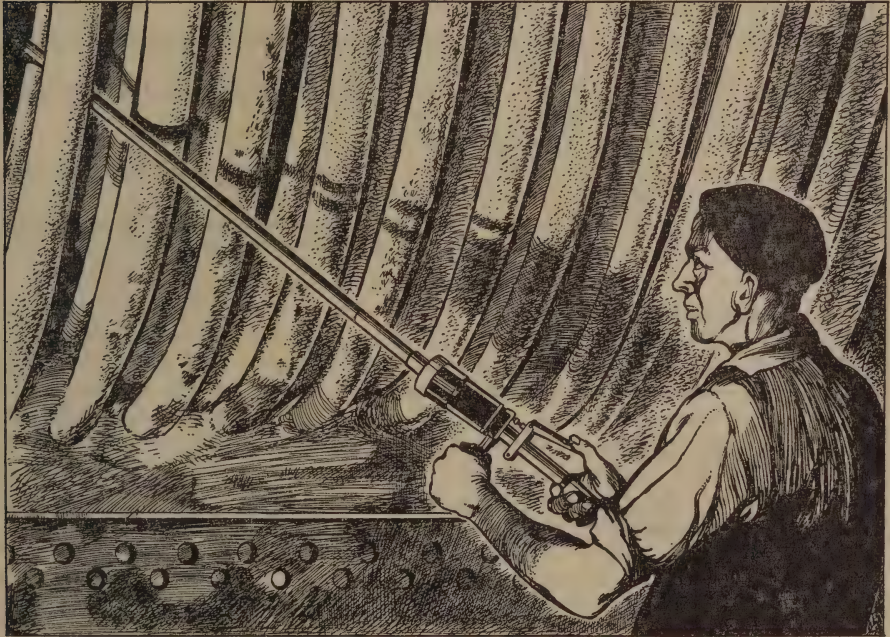


FIG. 16. Tube cleaning by percussion lance.

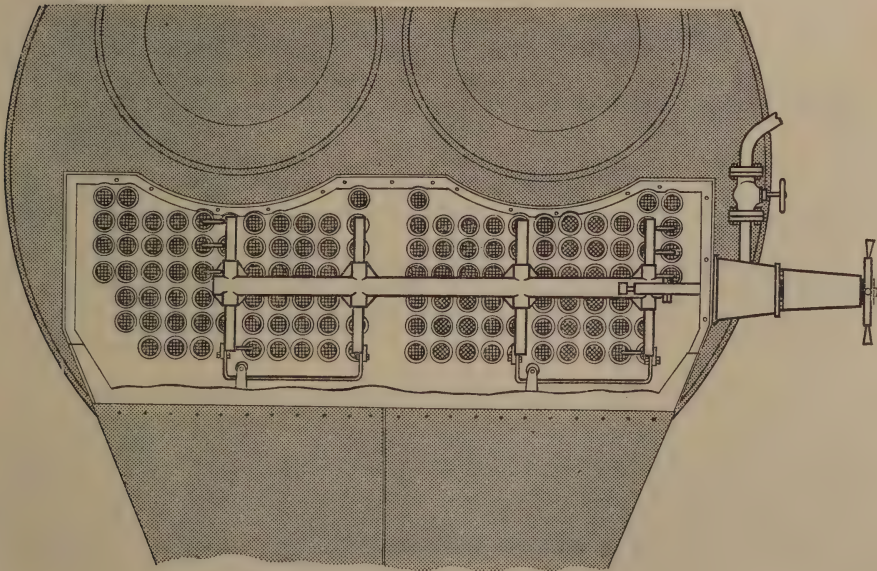


FIG. 17. Multi-jet soot-blower in boiler smoke box.

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CHAPTER 12

PULVERIZED FUEL

AND THE CYCLONE FURNACE

THE GAS TURBINE

PULVERIZED fuel firing is a method whereby the finely crushed fuel, generally reduced to a fineness such that 75–85 per cent. passes a 200 B.S. sieve, is carried forward by air through pipes directly to burners or to storage bins from where it is passed to burners. When discharged into the combustion chamber the mixture of air and fuel burns in a manner very similar to that of the combustion of a gas. The use of pulverized fuel has increased rapidly in Britain since the early 1930's and now constitutes the principal form in which coal is used in the generation of power by the British Central Electricity Authority.

The increasing proportion of fines in the coal raised since machine-mining became general has rendered pulverized fuel the most satisfactory way of using fine, low-grade coal.

There is less likelihood of bonded deposits accumulating on the heating surfaces than with stoker firing. Hence, the annual availability of a P.F. boiler is much higher. In addition, while there is, with stoker firing, a limit to the temperature to which the combustion air can be pre-heated, with P.F. firing the limit is much higher. This has an important effect on the overall cycle efficiency where regenerative heating leads to a high feed temperature.

The economic motives for the introduction and development of pulverized-fuel firing in power stations and large industrial furnaces can be listed as these:

- (1) Efficient utilization of the cheaper low-grade coal.
- (2) Flexibility in firing with ability to meet fluctuating loads.
- (3) Elimination of banking losses.
- (4) Better reaction to automatic control.
- (5) In furnaces, the ability to produce a high-temperature flame at the correct position.
- (6) High availability.
- (7) The ability to use high combustion air temperatures.

The installation of a P.F. plant to a boiler unit materially increases the capital cost; consequently larger boiler units are generally used with P.F. firing to reduce the proportional capital charges, but the more important justification for the adoption of P.F. firing on the larger installations, is that it is not practical to design, for stoker firing, boilers in the highest capacity ranges—say above 250,000 lb./hr.

PREPARATION OF PULVERIZED FUEL

SELECTION OF FUELS

Bituminous coal was the first fuel to be fired in pulverized form but subsequently the method has been applied to other coals. The fuels now successfully burnt in powdered form include bituminous coals, the semi-bituminous and anthracitic coals, hard pitch, and brown coal which may contain up to 65 per cent. of inherent moisture. The anthracites must, for reasons explained below, be more finely ground than the normal run of bituminous coals but unfortunately are harder and more difficult to pulverize. All fuels that are to be

pulverized must be nearly of quite dry, and this applies more particularly to the low-volatile fuels. If the coal is initially too wet the material may clog in the hoppers and feeders or even in the mill, which will suffer a reduction in output. The moisture that gives rise to these deleterious effects is the surface moisture, i.e. that which can be removed from the coal by air-drying, and not the inherent moisture which is removed by drying at over 100 °C. (Chapter 30). One of the first matters to be considered, therefore, is how the coal is to be brought into the proper condition for pulverizing. If the moisture content of the coal is not unduly high, it will be dried out sufficiently by the passage of pre-heated air (at 500°–700° F.) through the grinding mill. If it contains too much moisture to be dried in this manner an auxiliary drier is necessary.

DRYING THE COAL

It is always objectionable, but often unavoidable, for the coal entering the mills to be wet. The moisture is carried forward in the air-stream into the furnace where it lowers the flame temperature, increases the volume of waste gases, and in general has a deleterious effect on combustion; clearly it is desirable that the moisture content of the incoming pulverized fuel be as low as possible.

In order to enable the coal to be ground fine enough, its excess superficial moisture must be completely, or almost completely, removed. In the system most generally used this is effected by passing through the grinding mills the air, preheated as just explained, to 500–700° F., that is to be used in the combustion chamber as primary air. After pulverization, the dried-coal/air suspension leaves the drier at a temperature of about 150° F. This temperature is selected as being low enough to avoid any possibility of coking at the burner or pre-ignition of the coal in the pipeline between the mill and the burner, but high enough to avoid condensation of the moisture driven off in drying.

For sweeping through the mills, or for use as secondary air to assist and improve the combustion of the fuel in the furnace, hot air can be obtained by circulating it in cavity wall combustion chambers. Alternatively, the hot air, tempered if necessary by dilution with cold air, can be taken from an air preheater. If the superficial moisture in the coal entering the mill under the prevailing conditions is greater than can be evaporated by the primary air, the inlet temperature must be raised if possible, or the quantity of primary air must be increased and the secondary air supply to the furnace decreased. Ultimately, if no other measures are possible which will enable the coal to be dried sufficiently in the mill, the coal feed must be reduced. In exceptional circumstances, as when dealing with some very wet lignites, the coal can be dried wholly or partially in a separate drying plant.

CONVEYING AND STORAGE SYSTEMS

The two basic systems generally employed are: (a) the unit or direct-fired system, and (b) the central storage, or bin-and-feeder system.

THE UNIT OR DIRECT-FIRED SYSTEM

An example of the application of this system to a water-tube boiler is shown in Fig. 1. Raw coal is delivered at a controlled rate to the pulverizer. The primary air fan may be connected to the system at the discharge end of the mill when it serves to draw the preheated air through it, or in some designs the mill is operated under pressure, the fan being at the inlet. This latter arrangement has the advantage that the fan handles only clean air, as contrasted with coal-dust-laden air. The pulverized coal leaves the mill suspended in the

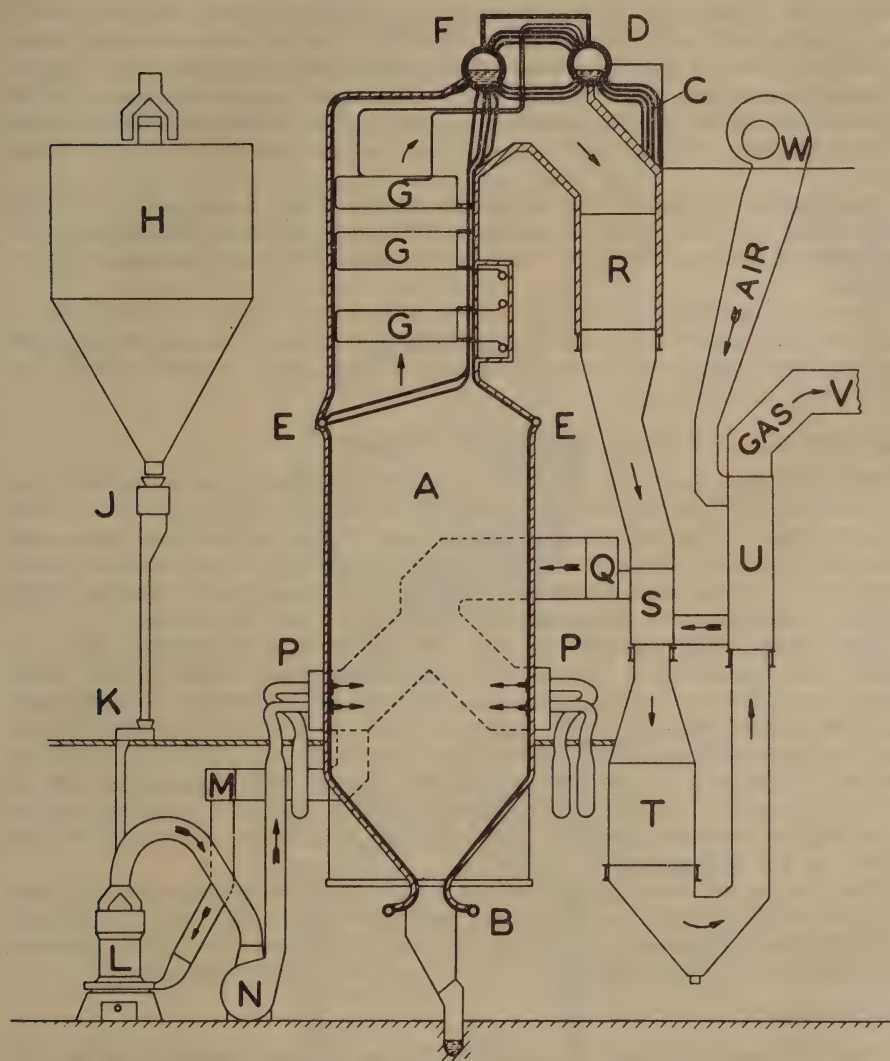


FIG. 1. Pulverized fuel firing of a water-tube boiler.

(A) Furnace. (B) Bottom headers supplying water to the furnace evaporating tubes. (C) External downcomer tubes taking the water from the rear boiler drum (D), a hundred feet above the basement level, to the headers (B). (E) Upper headers connected to the front boiler drum (F) by riser tubes which discharge the mixture of steam and water into the drum (F) where the steam is separated from the water and passes via the upper tubes into the drum (D) on its way to the superheater coils (G). The water delivered into the drum (F) passes via the lower tubes into the drum (D) where it mixes with the incoming feedwater before re-circulating down the tubes (C).

The coal supply gravitates from the storage bunker (H), through an automatic weigher (J) and feeder mechanism (K), to the pulverizing mill (L) in the basement. The coal is ground on a horizontal rotating table by three spring-loaded rollers running in contact with the layer of coal, while a continuous blast of hot air from the duct (M) dries the moisture out of it and transports the resulting powder, through the medium of the exhaustor fan (N), to each of the four corner burners (P).

After the evaporating tubes in the furnace (A) have extracted by radiation more than half of the heat generated by combustion of the fuel, the gases pass over the superheater coils (G), which they leave at a temperature of 1,000° F. to enter the economiser (R), which transfers some of the remaining heat to the boiler feedwater. From the economiser the gases pass through an air pre-heater (S), consisting of a number of thin metal plates separating alternate streams of air and gas into layers about half an inch thick. The heat extracted by the air heater is returned to the furnace in the combustion air to the burners (P) at 500° F. via the duct (Q). (T) and (U) are further sections of economiser and air heater, finally cooling the gases to 300° F. when they leave by the duct (V) to enter the ash precipitator (see Fig. 3). Air is extracted from the top of the building by the fan (W) and forced through the air heaters. There are two fans, together handling 150,000 cu. ft. of air (5 tons) per minute at a pressure of 8 inches water. gauge. (Courtesy, International Combustion Ltd.)

Heat recovery plant comprises economisers (R) and (T) and the air heaters (S) and (U), (Q) is the hot air duct to the burners (P), (W) is the forced draught fan and (V) is the gas duct to the precipitator and stack.

primary air stream and in this fashion is transported direct to the burner. The quantity and size of material removed from the mills is controlled either by a damper or by the fan motor speed ; the higher the velocity of the air through the mill the larger will be the particles that are carried away to the burner, but it is not wholly disadvantageous to have somewhat finer grinding at lower outputs, as this leads to greater combustion stability at lighter boiler loads.

It is essential, of course, that the mill and its auxiliary fan system be reliable in operation over long periods, produce pulverized fuel of a constant degree of fineness and maintain their performance when dealing with fuels of different qualities.

For very large steam generators several pulverizers may be provided, sometimes as many as five to one boiler, with their associated burners so arranged that routine maintenance can be carried out without interfering with the performance of the boilers.

THE CENTRAL OR BIN-AND-FEEDER SYSTEM

The coal in this system is passed through the pulverizers, air-swept with hot air as in the unit system, and is removed from the conveying air by a cyclone separator and is then deposited in storage bins. The pulverized coal is removed from the hoppers as required through feeders, normally of the worm or screw types, which pass it at the required rate into the primary air stream supplied by a fan which delivers the mixture through pipes into the burners.

The bin-and-feeder system is used for distributing pulverized fuel to a number of points from a central coal preparation plant. Since the air in the interstices of the coal contains moisture evaporated in the drier, this system is peculiarly liable to caking, with consequent difficulty in transporting the coal from the hoppers through the system and in maintaining a constant supply of fuel to the burners. Where the coal delivery line is very long, steps must be taken to avoid condensation. Feeding pulverized coal into an air stream at anything like a uniform rate is always difficult; it is easier to control the feed of coal to the pulverizers.

When the requirements for pulverized fuel are small, arrangements can sometimes be made to purchase it already prepared and in this event a bin-and-feeder system is necessary. Very little prepared P.F. is now available, however, and most users are large enough to have their own preparation plant.

RING MAINS

The ring main system is a modified bin-and-feeder system in which the pulverized coal is fed into a common main. The system is now mostly used in firing metallurgical furnaces. The pulverized fuel leaving the storage bins is suspended in an air stream, and the coal/air mixture is fed into the ring main system disposed around the works, from which a supply is given to the boilers or furnaces to be fired. Surplus coal is separated in cyclones and returned to the storage bins for redistribution.

CHOICE OF SYSTEM

The bin-and-feeder is not favoured in modern power stations, on account of dangers from explosion of coal/air mixtures and the tendency of the stored pulverized fuel to cake. In addition, maintenance costs, losses through vents, capital costs and operating costs are all against the system. Consequently the unit system will be adopted for most installations in the foreseeable future. The bin-and-feeder system still finds application in special circumstances, for example when firing several metallurgical furnaces on one works.

PLANT USED FOR PULVERIZING

The main types of mill in general use are:

- | Type | Working speed |
|---|--------------------------|
| (a) Ball, tube or rod (Kennedy, Thompson, Hardinge) | Slow: 20–40 r.p.m. |
| (b) Roller and table or bowl, roller and track (Loesche, Lopulco and Raymond) | Medium: 100–300 r.p.m. |
| (c) Ball and track (Babcock “E” type) | High: 1,000–4,000 r.p.m. |
| (d) Impact or beater (Kraemer, Attritor, Rema, Multiplex, Impax, etc.) | |

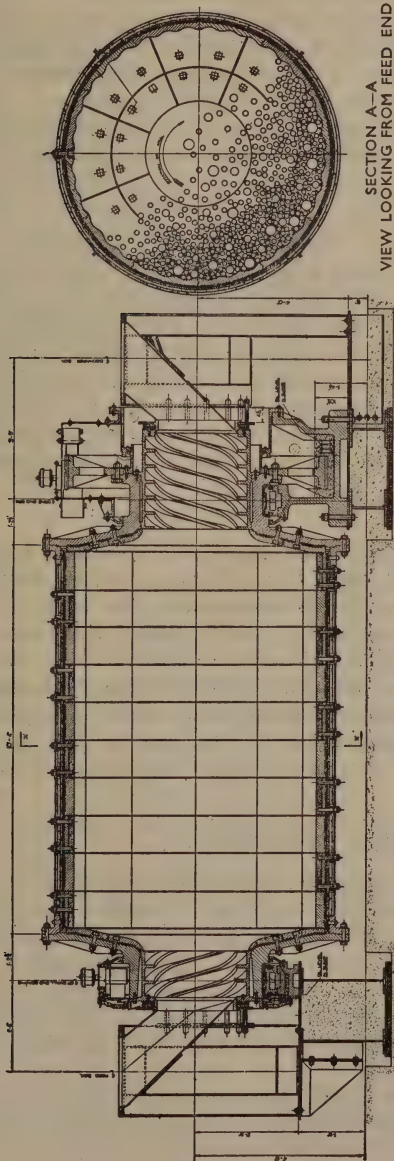


Fig. 2. Air-swept tube mill.

SLOW SPEED MILLS

The ball or rod mill illustrated in Fig. 2 consists of a steel drum charged with steel balls or rods, the drum being rotated at speeds varying between 20 and 40 r.p.m. The balls or rods are carried by centrifugal force up to a position from which they fall back on to the material to be pulverized. The mill is air-swept with pre-heated primary air as has been previously described.

The ratio length: diameter of this mill is usually $1\frac{1}{2} : 2$ and it occupies more floor space than other types, but routine maintenance and replacement of worn balls or rods can be effected without shutting down. A typical power consumption for pulverizing bituminous coal to the average fineness required, including the exhaust fan, is 40 to 50 kW. a ton.

One type of ball mill incorporates a vacuum system of classification and drying. The raw coal is fed into a pre-heated air stream and lifted in this stream to a classifier; here the fines are removed and the rejected larger particles fall back into the mill for re-treatment. This mill is claimed to reproduce the best features of the air-swept ball mill with reduced power consumption while making a finer product, and to be less sensitive to high moisture content in the coal.

MEDIUM SPEED MILLS

The coal is ground between rotating or fixed balls or rollers and a rotating or fixed table (see Fig. 3). The balls or rollers are spring-loaded and adjustable. These mills are air-swept. The product is conveyed to a stationary classifier, the oversize being rejected and returned to the mill. The degree of pulverization can be controlled by adjusting the separator. With identical outputs this type of mill is somewhat less sensitive than the ball mill to moisture in the fuel. The space occupied, capital cost and power consumption of these mills are slightly less than for the ball mill. They do not grind anthracite efficiently.

HIGH SPEED MILLS

High-speed mills reduce the coal mainly by attrition and impact applied by hammers or pegs rotating inside the casing at relatively high speeds. The grinding zone is generally a machined section and this type of machine (Fig. 4) in consequence requires more careful maintenance than other types previously described. The quality of the product deteriorates as the grinding elements wear and this type of mill is less suitable for dealing with anthracite or coal high in ash. Air sweeping is performed by a fan usually integral with the rotating crushing section. Space requirements and capital cost are less than on other machines, but power consumption is rather higher and the cost of maintenance much greater.

MILL INSTALLATION AND OPERATION

Magnetic separators should be installed to remove tramp iron from the feed of high-speed and medium speed mills and of some others, but are unnecessary with tube mills since the iron simply provides additional grinding material.

In installation, there should be provided good access for maintenance and renewals, and lighting and ventilation should be good. Pulverizing hard and abrasive fuels may involve frequent replacements and adequate gear should be available for dismantling and re-erection so that the work may be done expeditiously.

Any marked variation of the incoming coal in size, in moisture and ash content, or in grindability will affect the performance of the mill.

Some form of classifier should be installed at the mill outlet in order to ensure

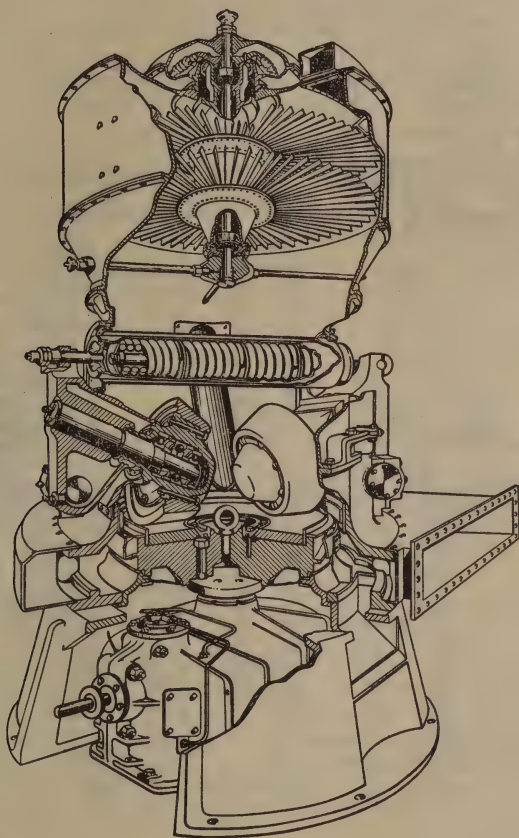


FIG. 3. Roll and table mill.

The rotating table is fed with raw coal which is pulverized on passing under the spring loaded rolls; hot drying air enters by the lower casing and rises through the mill under the pull of the exhaust fan, entrains the powdered coal which is classified by the variable speed rotating blade separator shown, the fine particles passing through to the exhaust and burners, the coarse returning to the mill table for further grinding.

uniformity of size of the product delivered to the burners and to return the oversize to the mill.

In steam generation for electricity supply, the following types of mill were in general use in 1954¹:

- (1) High- and medium-speed impact mills (such as the Kraemer).
- (2) Low-speed cascading ball mills (such as the Kennedy).
- (3) Medium-speed roller and table or bowl mills (such as the Loesche, Lopulco and Raymond).
- (4) The ball and track (i.e. the Petter and "E" types).

For bituminous coal in Britain and America, most of the milling plants in 1954 were of types (3) and (4) and were available in capacities up to 20 tons an hour. Types (1), (2) and (3) are generally arranged for suction operation and type (4) for pressure operation, but both cascading ball and roller and bowl mills have been adapted for pressure operation in America to suit pressurized firing units in that country.

THE GRINDABILITY OF COAL

The fineness of the final product is the most important measurement used in determining the performance of a pulverizer, and here the method of sampling becomes highly important. The British Standard method is used both to obtain the sample and to determine the classification of fineness. Uniformity of fineness of the pulverized coal is highly important in securing good combustion

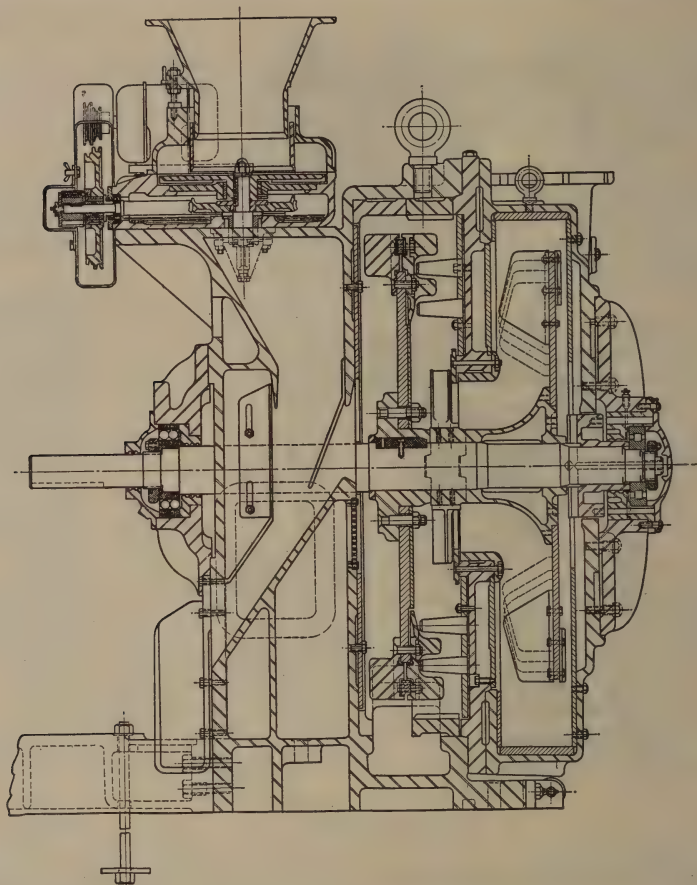


FIG. 4. Attritor drier pulverizer.

and, as will be clear from what has been said earlier, the finer the coal the easier it is to burn it completely within the furnace. The normal specifications call for the proportion of pulverized coal passing through a 200 B.S. mesh to be between 75 and 85 per cent. and within these limits the degree of fineness may be modified for bituminous or anthracitic coals according to the furnace conditions and to the grindability index. For example, when the pulverized fuel is to be used in the restricted and entirely water-cooled furnace of a shell boiler, it is essential that the product of the mill be as fine as possible, whereas in a large refractory-lined combustion chamber with suitably disposed burners the coal need not be so fine. Success in burning pulverized anthracite demands the highest degree and uniformity of fineness, the normal specification being 80-85 per cent. through a 200 B.S. mesh. Within limits, satisfactory combustion can be achieved with departures from this standard, but it is quite impossible to achieve satisfactory results with any coals fired as a coarse product. Emphasis should be laid upon *uniformity* of grinding rather than upon *fineness* of grinding, but within the practical limits of what can be fired successfully, the performance demanded from the mill should be determined by economic considerations, such as capital costs, maintenance charges and power consumption. The coal should not be ground finer than the process requires.

Coals of similar chemical composition may vary considerably in "grindability" and abrasiveness. Consequently attempts have been made to formulate a scale of "grindability values" with the object of assisting in the design and predicting the power requirements of pulverizing mills. These methods are based on comparison of the screen analysis of the coal under examination with that from a standard coal, both after pulverizing in a standard mill. The output of a commercial mill must clearly be related to the "grindability" of the coal fed to it.²

In the U.S. Ball Mill method the grindability index is determined from the number of mill revolutions required to reduce a sample of coal to the extent that 80 per cent. will pass through a 200-mesh B.S. sieve.

In the Hardgrove Mill method the grindability index is determined from the approximate percentage increase of surface of the final product in relation to the original surface, this relationship being calculated by an empirical method from the screen analysis.

PULVERIZED PITCH

Hard pitch is an excellent raw material for pulverized fuel, since it has a high calorific value, low ash and sulphur contents, and if stored in lump form is free from water. It is easy to grind, but as pitch softens under heat, harder pitches (softening point 100°C.—see Chapter 3) must be used and precautions taken against heating by friction during pulverization. Before being fed to the mill, the material should be roughly crushed into pieces below 1 in. in size, this operation being best performed by a spiked roll crusher. In order to avoid wetting during rainy weather, the pitch should be stored in lumps as received and the rough primary crushing should immediately precede pulverization.

The preparation and combustion of pulverized hard pitch follow pulverized-coal practice very closely, with the following differences:

(a) The pulverizer should be of the air-swept, impact type, and must be fed with cold air to avoid softening of the pitch. Edge-runner mills, ball mills, tube mills and others, with a positive grinding action, are unsuitable.

(b) Pipe lines conveying pulverized pitch should be suitably shielded and insulated from radiant heat.

(c) Ring-main systems such as those used for pulverized coal are not suitable for pulverized pitch.

(d) The burner nozzle must be a plain tube either air or water cooled. Spreader devices are not applicable.

(e) The velocity of flame propagation is of the order of 80 ft./sec. and burner nozzle velocities should exceed this figure.

(f) For the complete combustion of pitch, 200 cubic feet of air per pound of fuel should be allowed.

MECHANISM OF COMBUSTION OF PULVERIZED FUEL

Factors influencing the time required for the combustion of a particle of coal include coal properties such as rank and size, temperature, and aerodynamic conditions in the furnace into which the particle is injected.

Studies of the ignition and combustion of particles of coal injected into a hot furnace in a stream of air indicate that combustion takes place in three stages, (a) pre-ignition during which changes in shape and size (depending on the rank of the coal) and some evolution of volatile matter occurs, (b) ignition and combustion of the volatile matter, (c) combustion of the residual carbon.

The behaviour of particles of caking, non-caking coal and anthracite differ greatly during the initial stage. Caking coals become soft or plastic and the particles are blown into tiny ballons having very thin walls, first noted by Sinnatt and termed by him *cenospheres* the size of which is determined by

the nature of the coal and the rate at which it is heated. The higher the temperature in the ignition zone, the more rapid is the ignition and the smaller is the size of the cenospheres formed from the caking coal. Large cenospheres are more difficult to burn than small ones because their larger surface results in more rapid loss of heat.

Weakly caking or non-caking coals (group 700–900) and the low volatile coals and anthracites (group 100–200) do not form cenospheres on heating. Some fragmentation of the particles occurs due to the rapid rate of heating in the ignition zone, particularly in the case of the group 700–900 coals which have a high volatile content. The solid residue or 'coke' from these coals is much more reactive than that from the group 100–200 coals.

Although it is probable that the coal particle ignites at a lower temperature and hence before the volatiles, combustion of the solid residue takes much longer. The overall burning time of a coal particle is mainly dependent therefore upon the time required for burning out the solid residue remaining after the evolution of the volatiles. The rate of combustion of the solid particle depends mainly on its temperature, assuming of course that the aerodynamics of the furnace are such as to ensure an adequate supply of oxygen for its combustion. Above a certain temperature (800–1,100° C.) which varies with the nature or reactivity of the residue, the rate of combustion depends on the rate of diffusion of oxygen to the surface of the particle. Below this temperature the rate of combustion depends upon the rate of the reaction between the carbon and oxygen, which decreases rapidly as the temperature declines. If, therefore, a particle is cooled by its surroundings much below 800–1,100° C. the rate of burning declines rapidly.

During combustion a particle is surrounded by an "atmosphere" of combustion products through which the oxygen has to diffuse to react with the carbon. Experiments have shown that the time for the combustion of a 200-mesh (76 μ) particle of coal containing 30–40 per cent. volatile matter is approximately 0.3 second, and that the time required for combustion varies approximately as $d^{1.5}$, d being the diameter of the particle. Higher burning rates can be attained with relative motion between the air and the burning particle to increase the rate of diffusion to the carbon surface. With small particles however, as is mentioned later, this is difficult to achieve as the particle rapidly achieves the velocity of the airstream into which it is introduced.

Since the solid residue from low volatile coals and anthracites is relatively unreactive, these fuels are more difficult to burn than coals of lower rank. Consequently they should be more finely ground and used with less excess air, whilst heat losses should be avoided by providing refractory walls backing the ignition zone. These precautions are essential to secure satisfactory operation.

THE COMBUSTION OF P.F. IN PRACTICE

BURNERS

The main requirements of a burner are that it shall ensure rapid and intimate mixing of fuel and air, and maintain an adequate supply of oxygen surrounding each fuel particle until its combustion is completed. The need for intimate and rapid mixing of fuel and air within the furnace dominates the design of the burner. According to whether a short or a long flame is required the burner is designed for turbulent or parallel flow.

Burners embodying turbulent flow, one of which is illustrated in Fig. 5, are designed to produce an intense short flame by creating turbulence within a limited distance of flame travel by means of active impingement of jets of secondary air on the main stream of primary air/fuel mixture.

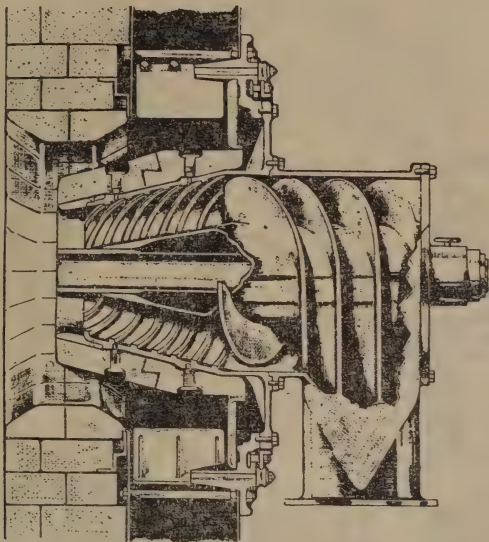


FIG. 5. Turbulent flow P.F. burner.

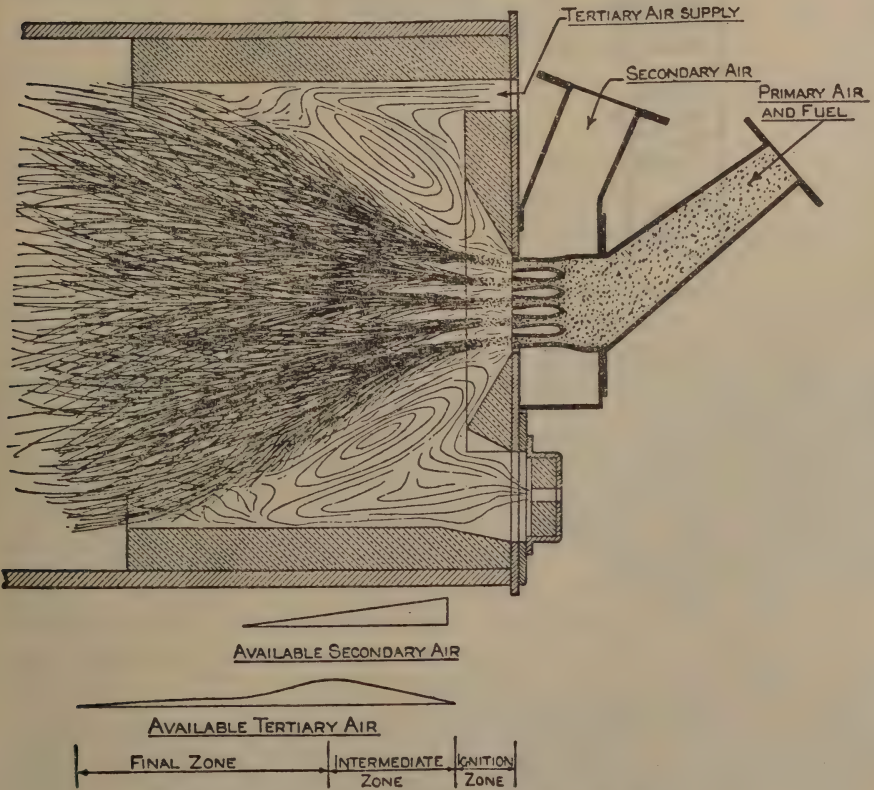


FIG. 6. Fuel Research Station parallel flow P.F. burner.

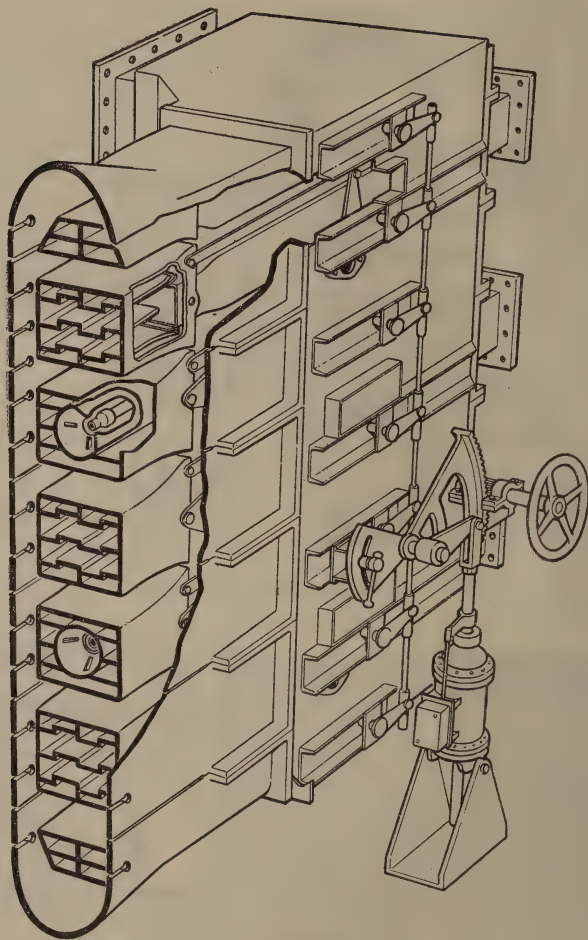


FIG. 7. P.F. Tilting burner for corner firing.

Parallel flow burners are illustrated in Figs. 6 and 7. Fig. 6 shows a burner developed at the Fuel Research Station. Fig. 7 shows an advanced design which was adapted for corner-firing in large steam generators and has resulted in the tilting burner by which the distribution of temperature in the combustion chamber and the super-heat temperature can be controlled (see later under "Combustion Chambers"). The main feature of this burner is that the mixture of air and fuel can be discharged from it either as strata or as jets interposed and surrounded by secondary air moving at different speeds relative to the fuel mixture.

In designing burners it is assumed that the coal/air ratio can be correlated with the rate of flame propagation. Any appreciable lack of balance between these two will cause either loss of ignition or back-firing. This is illustrated in Fig. 8 which indicates the speed of flame propagation with various fuel/air mixtures and with different types of coal. It will be observed that the maximum rate of flame propagation for low volatile coals is at a point where the air/coal ratio is low, and this ratio must be still further reduced for anthracite.

To a major degree the volatile content of the fuel controls the stage of ignition, which is the point where combustion becomes self-supporting. The

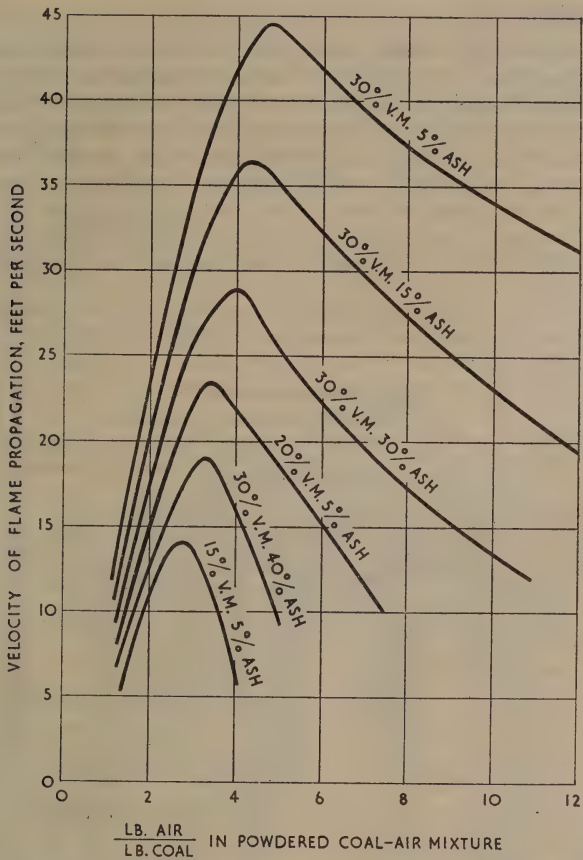


FIG. 8. Influence of coal rank on speed of flame propagation in P.F. firing.
Rate of flame propagation in powdered-coal-air mixtures.

temperature of ignition of bituminous coal is significantly lower than that of anthracite and this is another factor of which account must be taken in burner design. To overcome this difficulty, arrangements have been made in certain installations to extract part of the air from the fuel/air mixture at the burner by the use of an "air separation" burner, and to control the ignition by regulating the quantity of air extracted, the vented air being subsequently introduced into the combustion chamber at a suitable point as secondary air.

In direct-fired systems the air/coal ratio is important since the amount of air required for sweeping the mill and conveying the fuel may affect the composition of the air/fuel mixture at the burner. Some systems incorporate an additional air control which enables the composition of the fuel/air mixture to be adjusted and reduces the need to relate the burner design closely to the air-flow characteristics of the pulverizer.

FUEL DISTRIBUTION

It is important to secure uniform distribution of fuel to the several burners feeding a furnace and to avoid local differences in concentration. Attempts have been made to achieve this by situating the exhaust fans and fuel piping symmetrically in relation to the burners. These attempts have not been completely successful and mechanical distributors have been found to be necessary.

AIR PRE-HEATING

The importance of high furnace temperature to secure a high rate of radiant heat transmission from burning fuel to the receiving surfaces will be clear from the considerations explained in Chapter 9. Air preheat will help to heat the fuel more quickly and will thus enable the processes of distillation and combustion previously described to be completed in a shorter time. The main practical advantage of preheating air, however, is to reduce the flue gas loss.

It is impossible to prescribe exact temperatures for either the primary air or the secondary air. If conveying air is used for drying coal and also as secondary air the ultimate temperature will depend on the extent of drying

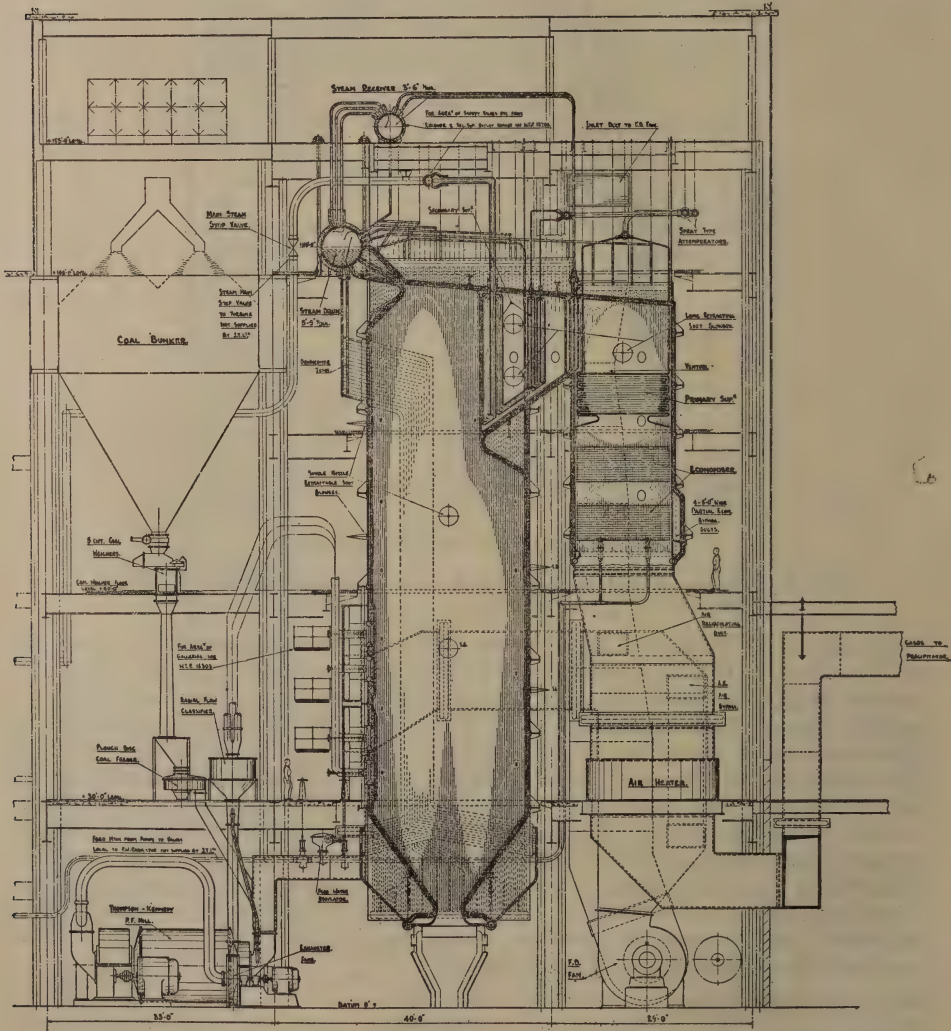


FIG. 9. Section through a water-tube boiler fired by pulverized fuel with front wall burners and using cascade ball mills.

effected. A very wet coal will, of course, be dried separately. Evaporation of the moisture in a moderately wet coal by the conveying air will in general

result in the upper limit of the temperature of that air when used as primary air being about 150° F. The use of a much higher temperature for secondary air is, of course, desirable, but here also there are limits according to the nature of the combustion cycle. An unduly high temperature cannot be used in the case of high volatile bituminous coals owing to the risk of their incipient distillation: with lower volatile coals and anthracites, of course, much higher temperatures are possible, i.e. up to 600° or 700° F³.

COMBUSTION CHAMBERS

The design of combustion chambers for water-tube boilers must take into account the need in a large installation to burn many different types of coal and the possibly wide range of ash fusion temperatures. Originally, it was believed that P.F. firing could be successfully applied only in large chambers. This is true for smaller boilers, but it is now known that the size of the furnace in larger units (say 350,000 lb. of steam an hour and over) is dictated not

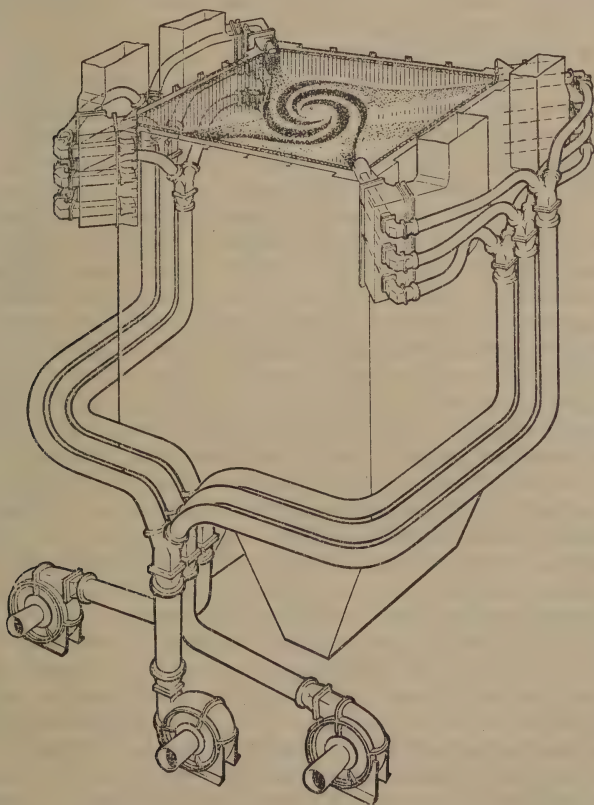


FIG. 10. Tangential corner firing applied to a large boiler furnace.

The furnace has three mills, each with its own exhauster and discharging to one burner in each corner. Note the resulting turbulent flame and the completeness of the furnace water wall cooling which extends from top to bottom of the furnace.

mainly by the volume needed for effective combustion, but by the area of surface necessary for heat absorption. Fluid ash carried in the gas stream is likely to be deposited on exposed metal surfaces and to solidify thereon as slag. Sufficient heat-absorbing surface must be provided to cool the molten ash by radiation below its softening temperature before it comes into contact with

metallic surfaces. Thus, in the larger units a tall furnace is used and in very large units it becomes economical to sub-divide the furnace either by water-cooled division walls or by arranging side-by-side, separately-cased furnaces.

Because of the rapid heat release from pulverized fuel and the high temperatures generated, care must be taken (a) to avoid over-heating the refractories (b) to transfer as much as possible of this heat to the heating surfaces proper, and (c) to avoid deposition of slag and dust on the heating surfaces. The combustion chamber may be lined with solid refractory, in which event heat release must be limited to what the refractory will stand. Alternatively, the combustion chamber may be built in refractory material having cavity walls within which air circulates. This arrangement not only assists in extending the life of the brickwork but provides a means of pre-heating the air used in sweeping the mills and for combustion (see Fig. 9). These systems are now used only for smaller units.

A third system of construction is that known as the "water-wall". Realising that a main problem was to protect the refractory brickwork, water-tube boiler designers placed around the combustion chamber, exposed directly to the radiant heat liberated by combustion, bare tubes conveying heated water to the convection heating surfaces and from there to the drums around the combustion zone. The burning fuel is thus surrounded by bare tubes having gaps of 3 in. or less between adjacent tubes, backed by refractory, thereby forming what is in effect chamber walls of water-cooled steel; the same effect is obtained by reducing the gap between the tubes with continuous fins welded to the tubes. This construction is now generally used in large P.F.-fired boilers. It has the special advantage of high heat transfer in the combustion chamber.

Heat releases up to 150,000 B.t.u./cu. ft./hr. have been obtained in small water-cooled combustion chambers in shell boilers, but it is considered that the heat release in solid-lined chambers should not exceed 12,500 B.t.u./cu. ft./hr. in refractory cavity-walled air-cooled chambers up to 15,000 B.t.u./cu. ft./hr. is permissible, and with water-walls up to 18,000 to 22,000 B.t.u./cu. ft./hr. It is doubtful how far it is of value to relate heat release to the volume of the combustion chamber; a more accurate designation would be the ratio of heat release to heat absorbed a square foot of projected radiant surface.

One of the main problems in pulverized-fuel firing is to shorten the time required for combustion. The development of combustion chamber design has been marked throughout its history by the endeavour to burn the maximum amount of coal dust in the minimum space and in minimum time. To this end, as already explained, means were sought for grinding the coal to a very fine subdivision at an economic cost. But for a given fineness, shortening of the combustion time is mainly the aerodynamic problem of bringing air and fuel together within the furnace as quickly as possible. This means that the air, waste gas and fuel particles must be in a state of violent motion, or turbulence, relative to one another. Early designers sought to achieve this through the use of burners causing a turbulent or whirling motion, skilfully introducing primary, secondary and sometimes tertiary air. Such burners promote quick ignition but it is a characteristic of pulverized-fuel firing, in distinction to stoker-firing, that it is extremely difficult to influence the tail of combustion. This cannot be done by burner agitation or by introducing secondary air at points farther along in the path of the burning dust. The intense motion needed is secured in modern practice by multiple burners, situated for example (as shown in Fig. 10) in the corners of the combustion chamber, or in the roof, or by tilting burners which are adjustable, all arranged so that streams of burning fuel and air impinge violently on one another.

Fundamentally for a given size of particle heat transfer and air : fuel ratio there is a maximum combustion intensity which cannot be exceeded, unless

there is relative motion of a high order between the fuel particle and the air.

ASH AND DUST

The types of pulverized fuel furnaces in use can be distinguished also by the methods adopted for ash removal. In Britain, the great majority of installations are of the "dry-bottom" type, in which ash particles are cooled by radiant heat interchange with surrounding surfaces to below their softening point and the smaller particles are conveyed from the system entrained in the gas stream. The larger particles and the clinker are deposited on the dry bottom of the combustion chamber and removed by means of a low- or high-pressure hydraulic system. In the low-pressure system, there is a constant deposit of ash into a continuous sluice below the throat of the combustion chamber. The high-pressure system operates intermittently and the accumulated ash is flushed by high-pressure water jets, located in the hopper, into the normal sluice channels. With dry bottom furnaces about 10 or 20 per cent. of the ash is extracted from the furnace bottom. To keep the heat content of the gases entering the convection surface as high as possible while restricting the gas temperature to suit the ash characteristics, flue gas has been recirculated from the economizer outlet back into the stream of hot gases leaving the furnace.

The second type is the slag-tap furnace in which the ash flows molten from the combustion chamber into a tank of water below, where it is converted into an easily handled product which can be used for road filling, as a concrete aggregate and for brick making. With this method, low-fusion-temperature ashes present no difficulty and in general it permits higher furnace temperatures, higher combustion rates and consequently increased boiler output. The generally higher ash-fusion temperatures of British coals has up till now somewhat limited the development and adoption of the slag tap furnace in Britain. Some 45-50 per cent. of the ash is extracted as slag. The amount of ash melted out in both dry and wet-bottom units has been further increased by re-firing fly-ash caught in the dust-collecting plant. After the dust has been collected it is usually handled by some form of air suction system.

The third type is the cyclone burner, described below. Using this burner, some 85-90 per cent. of the ash is extracted in the molten state.

Pulverized fuel-fired furnaces must be provided with efficient auxiliary plant for arresting the grit and dust inevitably carried in the exit gases. This may be effected by washing, e.g. as practised when cleaning blast furnace gas, but in boiler practice generally involves installing a mechanical separator, followed usually by an electrostatic precipitator.

The problem of grit and dust removal exists with all plant burning solid fuel, but is most acute when burning pulverized fuel. "Grit" may be defined as the larger air-borne particles which generally come to earth near the source of emission, while "dust" comprises the fine particles that are readily air-borne and remain suspended in the atmosphere for some considerable period. All the grit should be removed from medium and large installations but no plant will remove all the dust; electrostatic precipitators, even when in perfect order, allow 2 per cent. of the finest dust to escape. When stating the efficiency of dust removal by any plant it is essential to state the limits of size to which the figure refers. Particles greater than B.S. sieve size 200 (0.076 mm.) are distinctly gritty, whereas particles having a size equivalent in free falling speed to solid particles of ash less than 20 microns (0.020 mm.) are so fine that they remain suspended almost indefinitely in natural air currents and hence behave in the precipitator as a gas.

APPLICATION OF P.F. FIRING TO SHELL BOILERS

P.F. firing is now being applied to Lancashire boilers. Here it is essential that

the burning fuel shall not be chilled by the adjacent cold surfaces. Heat release figures of 150,000 B.t.u./cu. ft./hr. are on record and inferior grades of coal have been burnt successfully with methods of control similar to oil firing and at high efficiency.

Ash deposits arising from the use of P.F. in Lancashire boilers are removed by steam nozzles placed in appropriate positions in the furnace tubes and flues and operated when required. The accumulated ash is collected in a chamber designed for the purpose and is sprayed with water before removal.

METALLURGICAL APPLICATIONS

Pulverized fuel finds many applications in the metallurgical field. As compared with other forms of solid-fuel firing, P.F. is found to economize in labour and fuel, while the improved control of furnace temperatures has a good effect on the quality of the finished product.

ANNEALING FURNACES

Pulverized fuel firing is used successfully for annealing steel and malleable iron castings, reducing scale losses and improving output. Its application to malleable castings is relatively simple and may be relied upon to give a satisfactory anneal, with low fuel costs.

For supplying pulverized fuel to a number of furnaces on a single works, bin-and-feeder and ring main systems are commonly used. Typical fuel consumptions for furnaces reasonably well loaded, including castings, ore packing and pots, are 10 cwt. a ton of black heart castings annealed and 12 cwt. for white heart castings.

SMALL FORGE AND DROP STAMP FURNACES

Many of these furnaces are fired by pulverized coal. The size of the furnace varies from the small bar furnace having working ports only 18 in. long to the larger door type suitable for cut lengths of billets having a cross section varying between $2\frac{1}{2}$ in. square and 18 in. square; for these extremes the hearth sizes would vary from 2 ft. 6 in. \times 5 ft. to 12 ft. \times 6 ft.

When operating bar furnaces, the width of which generally varies between 18 in. and 2 ft. and the length up to 12 ft. according to the number of ports used, the fuel consumption a ton of stampings can be as low as 8 to 10 cwt.

Much depends on how efficiently the furnace is worked and also how efficiently the hearth area is stocked with bars.

HEAVY FORGE FURNACES

Blooms for serving both hammers and pressers are heated by pulverized coal in furnaces ranging from multiple small units dealing with 5-ton ingots up to 50- and 100-ton ingots.

There are two main methods of applying this system of firing to forge furnaces; one is to cross-fire into a side combustion chamber or two such chambers, one on each side of the furnace, allowing the gases to follow the contour of the roof in their normal flow. The alternative and more direct method is to apply the burners in the back wall of the combustion chamber and fire over the top of the ingots, care being taken to avoid direct flame impingement on the stock particularly with alloy steels.

Care must also be taken to avoid the deposition of fine particles of ash on the metal, as if this occurs the ash will be forced into the metal under the hammer and give a faulty forging. This difficulty can be reduced to a large extent, where space permits, by burning the fuel outside the stock in pre-combustion chambers installed as an integral part of the furnace. Many faults

can also be reduced or even entirely eliminated by ensuring consistently fine pulverization of the fuel so that the ash particles are entrained and carried away in the gases leaving the furnace.

CONTINUOUS FURNACES

Pulverized coal has been applied to many types and sizes of continuous furnaces in the steel industry with outputs varying from $\frac{1}{2}$ ton to 15 tons an hour. For heating mild steel, two or more burners are generally placed in the rear or combustion wall of the furnace and directed in a line parallel to the lie of the stock. The design of furnaces for specific purposes such as the production of solid-drawn tubes or other types of piercings is a specialist undertaking, but in both cases the essential objective must be that the steel shall be well-soaked. As an alternative to a high rate of heat input at the discharging end, boosting burners can be placed half-way along the furnace.

The design of furnaces is treated in Chapter 20 where the general conditions of design for satisfactory performance are discussed; these conditions apply equally to pulverized-fuel firing.

MELTING FURNACES

Pulverized fuel is extensively used for melting special alloy irons for the production of rolls, the furnaces used being of the reverberatory type with burners placed in the back wall of the combustion chamber. These furnaces are claimed to give excellent results, with fuel consumptions in the region of 10 cwt. a ton. Air and rotary furnaces are also used when melting iron for the production of malleable castings, but here the temperatures involved are generally somewhat higher with a corresponding increase in consumption. The Bracklesburgh Rotary furnace employed for this purpose uses anthracite entirely, while the Sesci type is lighted with bituminous coal and is subsequently operated on anthracite.

OTHER METALLURGICAL APPLICATIONS

The largest installations are found in copper smelting and there are in America furnace outputs up to 750 tons a day, whereas in Britain applications in the non-ferrous industry have been restricted to smaller furnaces with capacities up to 20 tons a day, again particularly in copper smelting. The burners, usually not less than two in number, and of an adjustable swivel type, are installed at the end of the furnace, opposite to the skimming door.

The process cycle usually covers 24 hours, at temperatures varying between 1,100° C. and 1,300° C., with a casting temperature about 1,200° C. During the earlier part of the cycle an oxidising atmosphere is maintained, with a neutral or reducing atmosphere during the later stages. Substantial savings are claimed in fuel consumption as compared with other types of solid fuel firing.

Pulverized fuel has been applied successfully to batteries of lead melting pot furnaces fired from a bin-and-feeder or ring main system. There is also a record of application in the lead smelting industry to the slag-foaming process for recovering lead and zinc from lead blast-furnace slag, whilst reverberatory furnaces in the tin industry have also been fired by pulverized fuel.

The system employed for the combustion or flash roasting of sulphur-bearing materials, for example pyrites concentrate containing 40–50 per cent. sulphur, whilst not strictly pulverized fuel firing resembles in many respects a normal pulverized-fuel-burning installation.

OTHER APPLICATIONS OF PULVERIZED FUEL

CEMENT MANUFACTURE

The application of P.F. firing to the rotary cement kiln provides no particular problem. The kiln consists of an inclined refractory-lined steel cylinder, varying in diameter from 6 ft. to 12 ft. and in length from 100 ft. to 500 ft., rotating about once a minute. The burner is situated at the lower end and the mixture of limestone and clay fed in at the upper end is caused to gravitate by the rotation to the lower end where it is discharged as clinker. Carbon dioxide is liberated from the limestone en route. Much of the ash from the fuel becomes incorporated in the cement.

LOCOMOTIVES

Attempts have been made to fire locomotives by pulverized fuel (a) by fuel prepared at a central plant and supplied ready for use to a hopper carried on the tender and (b) by a direct pulverizing plant situated on the tender. System (a) has been more generally adopted as being simpler and involving no problems of loading and rail gauge. These attempts have met serious difficulties from the accumulation of ash in the combustion chambers and tubes.

MARINE VESSELS

By 1955 some 17 vessels throughout the world had been, at one time or another, converted to P.F. firing; two of these were fitted with water-tube boilers and the remainder with single- or double-ended Scotch Marine boilers.

Difficulties were encountered by reason of slag and ash deposits and the variability of the fuels. The shorter, and generally greater number of tubes, complicated by the return tubes, set up special problems in the Scotch marine boiler, while any variation in the fineness of the fuel results—as in land installations—in faulty distribution to the burners and poor combustion. The competition from oil makes it unlikely that pulverized solid fuel will be used afloat to any extent.

COLLOIDAL FUEL

Colloidal fuel is a stable atomizing fuel containing up to 30–35 per cent. of solid fuel in pulverized form held in suspension in oil. This mixture can be fired and burned virtually in the same way as a liquid fuel without any fundamental change in a standard oil-firing installation. The relative value of colloidal fuel and oil depends on price and calorific value; with present prices of coal and oil there would seem to be little reason for using colloidal fuel.

Technically, colloidal fuel has attractions: It can be pumped, stored and burned like oil, although the permissible duration of storage may be limited by the stability of the suspension; it enables better use to be made of storage space than with coal and there is no risk of spontaneous combustion; the ash and moisture content are less than with coal, though greater than with oil. Colloidal fuel may be prepared by pulverizing the coal in the normal way and mixing it with the oil, or by first rough grinding followed by final grinding in the oil to achieve the best mixing; one of the problems is to “wet” the coal particles effectively with oil in order that the suspension shall be reasonably stable.

In practice, the two components of colloidal fuel tend to burn separately, the oil first and then the coal; an adequate supply of air must therefore be delivered at a low level across the furnace floor to burn the carbon particles before they leave the combustion chamber. Whilst there seems little likelihood that colloidal fuel will find major application under present economic circumstances the technical details of preparation and use appear to have been solved.

THE CYCLONE FURNACE⁴

This furnace does not normally burn fuel which in the strict sense of the term is "pulverized", but burns coal crushed below $\frac{1}{4}$ in. under conditions of intense turbulence in a comparatively small water-cooled chamber in which the temperatures are sufficiently high to melt the ash, which then runs down the furnace walls in a fluid state to the outlet. Heat releases are of the order of 500,000–600,000 B.t.u./cu.ft./hr. and coals with high ash-melting temperatures have been used. The cyclone furnace seems likely to find wide application, particularly since most of the ash is retained in the slag. Although not strictly pulverized-fuel-fired, it will be convenient to describe the cyclone furnace here. One type, the German K.S.G., is designed specifically for firing by coarsely pulverized fuel.

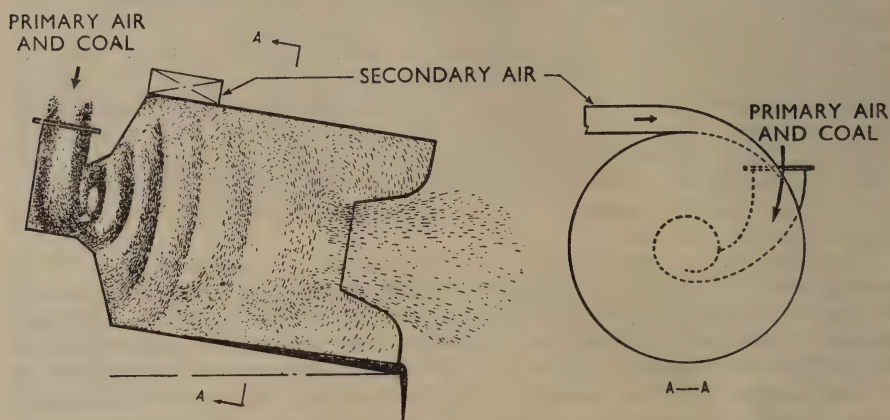
The principle of operation of a cyclone burner is similar to that of the vortex burner, patented by Lander in 1929. In this, centrifugal force kept fuel particles rotating in fixed circles according to their size in equilibrium against the drag of the inwardly spiralling air, so that relative motion between air and fuel accelerated combustion. In the cyclone furnace the proportions of the chamber and the velocity of the air are such that particles having a higher centrifugal momentum than a certain chosen value, are thrown outwards on to the walls. The use of pre-heated air (600–750° F.) and air fuel ratios approaching the theoretical results in high temperature in the chamber and the ash melts. The larger coal particles are restrained by the slag layer and relative motion between them and the air results in rapid combustion of the particles.

In the cyclone furnace, the radius of the walls is chosen so that the larger particles, having the higher centrifugal momentum, are thrown outwards on to the slag-coated walls, and are held on the walls, thereby greatly increasing the relative velocity between fuel and air and causing the fuel to burn rapidly. The high temperature thus engendered keeps the surface slag molten so that it runs down to a hole from which it is tapped. The primary aim of the cyclone furnace is to retain as much as possible of the ash in the furnace itself from which it is tapped in the liquid state as just described.

The introduction of the cyclone furnace gives reasonable expectation of obtaining:—

- (i) a considerable reduction in the amount of ash deposited on boiler heating surfaces;
- (ii) a reduction in the size of the furnace and boiler unit, because of the high furnace heat release rates;
- (iii) simplification of equipment for removal of dust from flue gases;
- (iv) a reduction in fuel preparation costs, since the cyclone furnace should burn comparatively coarsely crushed fuel instead of the finely ground coal required for pulverized-fuel firing;
- (v) a reduction in the amount of ash passing into the boiler should eliminate the need for hand-lancing of heating surfaces; this would make it possible to operate the boiler with positive pressure on the gas side;
- (vi) a smaller boiler, with simpler equipment, particularly for fuel preparation and flue gas cleaning, which could be accommodated in a smaller building;
- (vii) the production of coarsely granulated ash more easy to dispose of than the fine ash, mainly in suspension, from dry-bottom pulverized-fuel-fired boilers—a virtue shared with other types of slag-tap furnace—but a larger proportion of the ash is recovered in this form in the cyclone furnace.

Fig. 11 illustrates diagrammatically the working of the horizontal cyclone furnace. Primary air and coal, crushed to pass $\frac{1}{4}$ in. mesh, are admitted through a scroll at the outer end of the cyclone chamber and enter it with a



THE CYCLONE FURNACE

FIG. 11. Simplified representation of a cyclone furnace

swirling motion; secondary air enters at the periphery, tangentially to maintain the swirl. The wall of the chamber is built up from water tubes, studded on the inner face and covered with a suitable plastic refractory, and the gas outlet throat has the form of a re-entrant cone, which reverses the axial motion of the gases and forces them radially inwards before they leave the furnace.

Slag deposited on the chamber walls dissolves away the initial refractory coating to a depth where the cooling effect of the tubes prevents further action. The cyclone chamber is then lined with a layer of slag which reaches an equilibrium thickness for a given furnace heat release rate because, at some thickness determined by tube temperature (almost constant), slag conductivity and flame temperature, the surface temperature of the layer will be above the flow temperature of the slag, so that additional deposits will run down the walls. Refractory maintenance in the cyclone chamber is therefore negligible, since the refractory which best withstands attack of coal-ash slag is the slag itself and this is in fact being constantly renewed.

In most of the horizontal cyclone furnaces at present being installed on the Continent (Europe) the primary air and coal are admitted through ports just below the secondary air inlets, and the coal is crushed to pass $\frac{1}{16}$ in. mesh. This method of introducing the fuel is also being adopted in most installations in Britain.

CYCLONE AND BOILER

A typical arrangement of a horizontal cyclone connected to a boiler combustion chamber is shown in Fig. 12.

The boiler chamber is divided by a screen of water-tubes, closely spaced, studded and refractory-covered above and opposite to the cyclone outlet. Lower down, the tubes are spaced to form an open screen leading into the second part of the boiler chamber, in which the gases are cooled by radiation before they enter the convection passes of the boiler.

The slag screen traps particles of fly ash leaving the cyclone and, by deflecting gases downwards and by acting as a reflecting arch, keeps the floor of

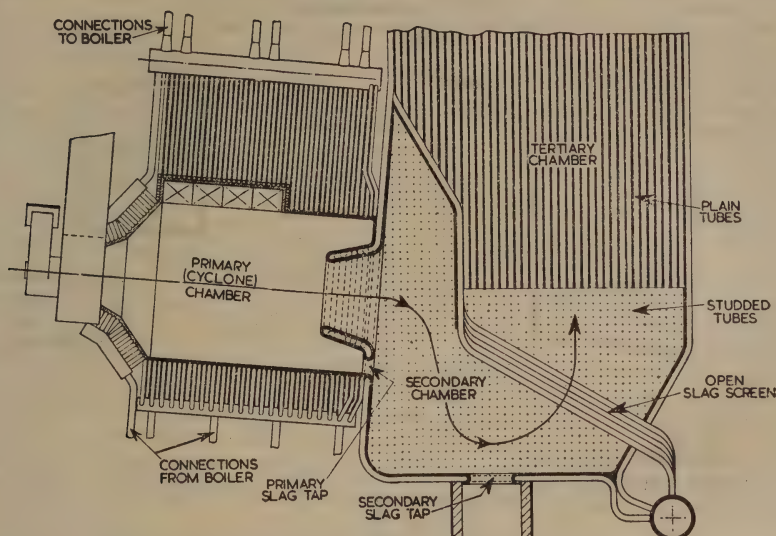


Fig. 12. Cyclone furnace applied in firing a water-tube boiler.

the secondary chamber hot. Slag from the cyclone and from the screen runs on to the floor of the secondary chamber, from which it flows into a water-filled sump where it is granulated.

Vertical cyclone chambers may be arranged to discharge gases vertically downwards with the slag into a secondary chamber or, under the boiler, vertically upwards into the boiler combustion chamber; in this case slag is discharged downwards directly into a water sump and there is usually no division of the boiler into secondary and tertiary chambers.

Control of the cyclone furnace presents no great difficulty. A master controller regulates the flow of fuel and air in parallel to suit the load. The air: fuel ratio must be kept at the required value to ensure that slag flow is maintained, in which respect the requirements of the cyclone furnace are more exacting than in dry-burning P.F. practice. The air is regulated by dampers or fan speed or both, in the conventional manner. The supply of coal to the cyclones is controlled by the speed of the feeders. The coal crushers operate for long periods without maintenance, but in emergencies, continuity of steam generation is not affected because individual crushers and cyclones can be shut down if necessary. Three cyclone furnaces are needed to supply a steam generator of 600,000 lb./hr. capacity.

The cyclone furnace is not applicable to all fuels; present experience (1956) is that between the limits of too high an ash fusion temperature, over about 2,500° F., and too low a volatile content, a considerable range of coals is suitable for this method of firing, but a decision in any particular case can safely be based only on practical tests on a small cyclone of, say, 2 ft. diameter and 2 ft. long.

A unit recently (1956) put into commission by the British Central Electricity Authority at Barking "C" station is a natural circulation Radiant boiler with three 8 ft. diameter cyclone furnaces. This unit is suitable for an evaporation of 540,000 lb. of steam an hour at 950 lb./sq. in. and 940° F. The fuel will consist of a variety of bituminous coals with a gross calorific value of 10,500

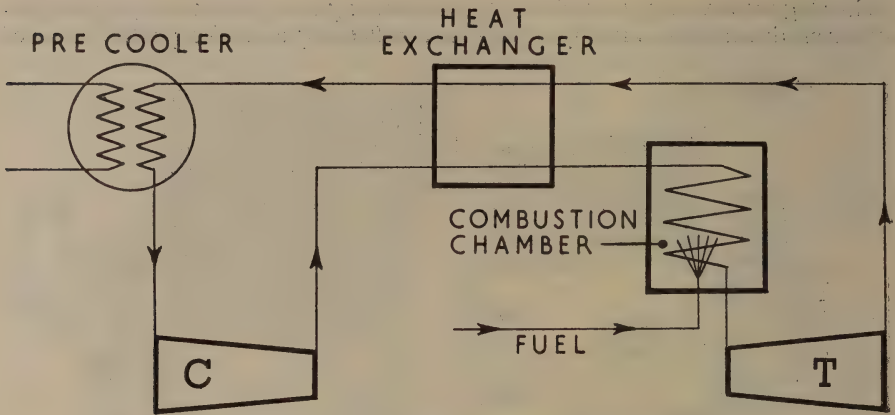


FIG. 13. Closed cycle.

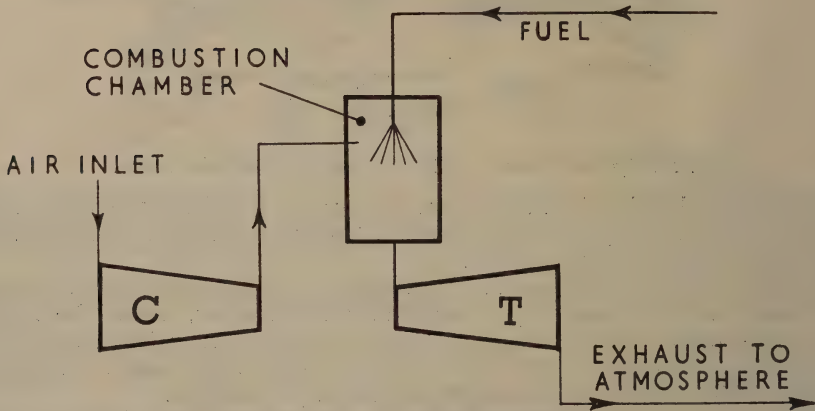


FIG. 14. Open cycle, simple system.

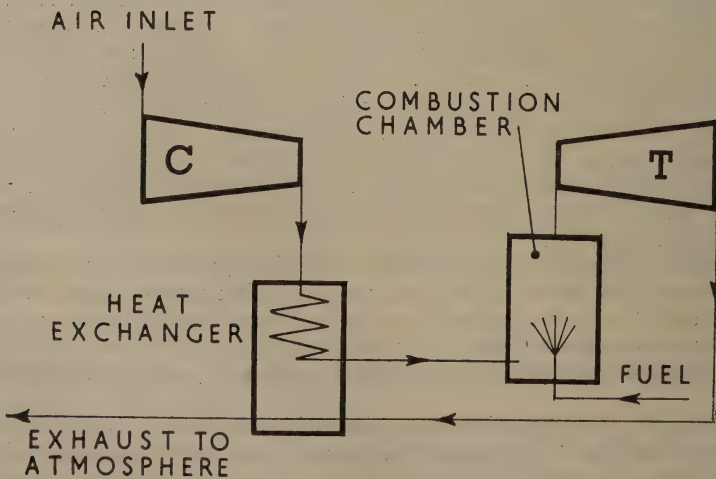


FIG. 15. Open cycle with heat exchanger added.

DIAGRAMMATIC REPRESENTATIONS OF GAS TURBINE.

B.t.u./lb. This boiler is designed to give 20 per cent. more evaporation than conventional boilers occupying the same floor area.

THE GAS TURBINE

In Britain the Ministry of Fuel and Power initiated experiments in the application of coal-burning combustion chambers to gas turbines, the ash being removed either "dry" or after being allowed to become molten, as in the cyclone furnace. The problem was essentially one of applied research and development, and received the financial support of the Central Electricity Authority and the National Coal Board. Because it was concerned with application it was conducted largely by firms with the assistance of the British Coal Utilisation Research Association and the Fuel Research Station. Similar developments, perhaps not so broadly based, have been conducted in Australia (on brown coal combustion) and in America and Canada (on the application of coal burning to a gas turbine locomotive). The general interest in these developments follows from the fact that the gas turbine is usually cheaper in capital cost, makes less demands for water cooling, and can be made in smaller efficient sizes than a steam turbine. It has lower maintenance costs than the compression ignition engine, can be constructed over a larger range of sizes, and is more easily adapted to coal burning because the burning times allowable are limited only by the size of the combustion chamber and not related to the speed of the engine.

As a result of experiments in Britain and abroad, coal-burning combustion chambers with good efficiencies and flexibility of operation can now be designed and the present combustion control and gas cleaning arrangements are adequate for operation with air heaters (as in the closed cycle and some locomotive designs). There is every expectation that present running times on the open cycle can be considerably extended to the stage of economic application.

The relative merits of the various cycles have not been established and await further testing, but as might be expected from general considerations, the closed cycle (as shown in Fig. 13 with combustion equipment analogous to that of the steam cycle) presents an easier technical problem, since the turbine is not exposed to the products of combustion. Nevertheless, the air heater, while smaller than the boiler of a corresponding steam plant, uses expensive alloys and adds much to the capital cost of the plant. For this reason development is continuing on the open cycle, illustrated in Figs. 14 and 15. In Figs. 13-15, C and T represent cyclones and turbines respectively.

The function of the combustion chamber is to add heat to the working fluid—air. In the simple open cycle gas turbine, combustion takes place at a pressure of 4 or more atmospheres, and since the blade materials at present available limit operating temperatures to 700–750° C. when long life is required. The overall air : fuel ratio may be of the order of 50 : 1 up to 100 : 1, instead of 12–14 : 1 as in the case of a boiler. The desirable features of a combustion chamber for this application are good behaviour over the whole range of load, a shape suitable for air cooling without excessive pressure loss, and ability to use pre-heated air. (Compression to 5 atm. raises temperature of the air to 200° C. approx.; heat exchange will raise this to 350–400° C.) In addition, the chamber should be self-cleaning as regards ash removal. A high combustion intensity is also desirable to keep the size of the pressure vessels as small as possible.

It so happens that, in the open-cycle gas turbine, pressure varies with load, hence the velocity remains substantially constant. Consequently the residence time for a particle does not vary with load, and high combustion intensities are obtainable under pressure.

The problem of the preparation of pulverized coal and its delivery and burning under pressure has been solved with the aid of fluidization. As might be expected the outstanding difficulty is the prevention of more than negligible deposits of bonded ash on the blades and heat exchanger surfaces. Existing designs of gas cleaning apparatus have been adapted to gas turbines, and their high collecting efficiencies, particularly for particle sizes above 10 microns, has removed the risk of erosion and very much reduced the quantity of ash left in the gas stream approaching the turbine. This quantity can be further reduced by control of the coal preparation and combustion processes.

Both closed and open cycle gas turbines can be made in a wide range of powers, and their efficiencies can be increased by more capital expenditure on heat exchangers, intercooling, reheat, etc. These improvements are still in course of adoption in the oil-burning gas turbine and will undoubtedly find application in the coal-burning turbine in the event of the latter becoming practicable.

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Papers contributed to the Joint Conference on Combustion, held in Boston in June, 1955, and in London, Oct., 1955 (A.S.M.E. and I.Mech.E.). The *Proceedings* of the Conference, which cover a wide range of subjects, including pulverized fuel and the gas turbine, are published by the Institution of Mechanical Engineers.

CHAPTER 13

UTILIZATION OF LIQUID FUELS

GENERAL

THE liquid fuels that may be used in ordinary industrial furnaces and boilers are gas oil, light fuel oil, heavy fuel oils, coal tar fuels. The approximate specifications for these, except for coal tar fuels, are given in Table 1.

The following British Standards relate to the liquid fuels used for industrial purposes:

B.S. 209, Fuels for Oil Engines. B.S. 799, Oil Burning Equipment.

B.S. 742, Fuel Oils for Burners. B.S. 1469, Coal Tar Liquid Fuels.

B.Ss. 209 and 742 have been under revision for some time and are now superseded by B.S. 2869, Oil Fuels. Table 1 is based on that revised Standard.

TABLE 1

299 Table 1, the values given were those available at the time of going to press and before B.S.2869 had been published. Some of the values should be amended, viz.:
Viscosity, for 950 read 1,000.
Gross calorific values for fuels A, E, F, and G should read 19,200, 18,300, 18,150 and 18,000 respectively. (The net values are 18,000, 17,200, 17,100 and 17,000 respectively.)

Gas oil: A	.. .. .	45 secs.	20° F.	19,600
Light or Medium fuel oil: E	..	250 secs. max	35° F.	18,800
Heavy fuel oil: F	.. .. .	950 secs. max	70° F.	18,700
Extra heavy fuel oil: G	.. .. .	3,500 secs. max	..	18,300

Coal tar fuels are dealt with later in this chapter.
The effect on viscosity of heating these oils is illustrated in Fig. 1.

Liquid fuels have certain specific advantages:

- (a) the purchaser knows that the oil supplied will be consistent with the limiting specification applicable;
- (b) for any particular grade the calorific value is reasonably constant, whether calculated by unit weight or by unit volume;
- (c) they can be easily and compactly stored, safe from contamination, pilfering and spontaneous combustion, often in spaces otherwise of little value;
- (d) the rate of supply to the furnace is easy to control;
- (e) they can be easily metered;
- (f) there is no ash or clinker disposal problem;
- (g) liquid fuels are, so to speak, "fuels on tap" involving a minimum of the handling and supervision, disadvantages associated with the use of solid fuels.

Disadvantages that liquid fuels share with solid fuels are:

- (a) it is difficult to obtain without smoke the reducing atmospheres sometimes required in industrial practice;
- (b) it is commercially impracticable to remove certain deleterious substances, e.g., sulphur, from the fuel.

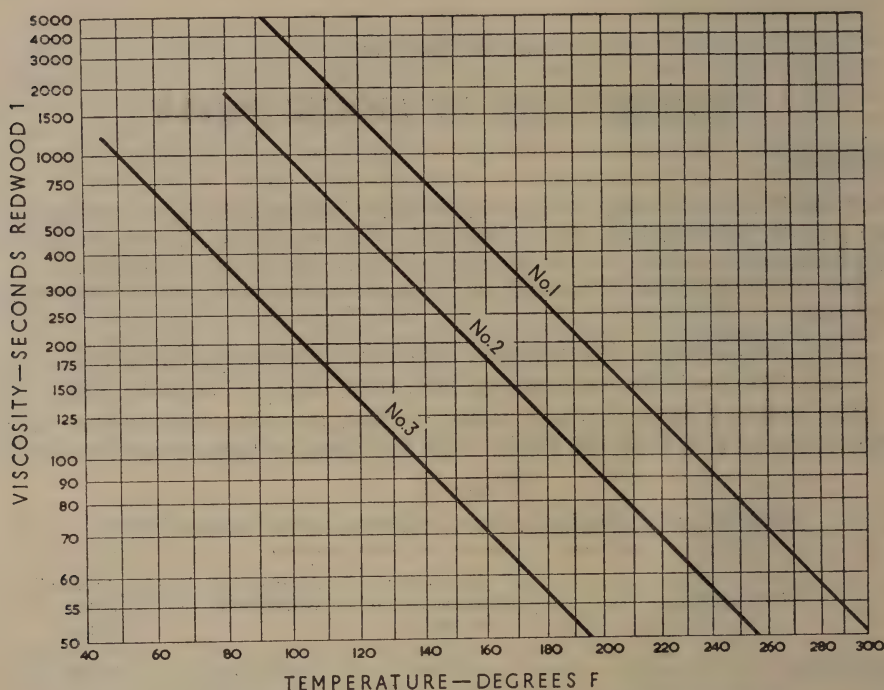


FIG. 1. Relation between viscosities of liquid fuels and temperature.

The three lines in the diagram represent oils of the following viscosities (Redwood No. 1 at 100° F.), namely—

No. 1	..	3,500 sec.
No. 2	..	950 sec.
No. 3	..	220 sec.

The approximate viscosity-temperature relationship for any other fuel oil, for which the viscosity at one temperature is known, can be determined by drawing through the known viscosity-temperature intersection a line parallel to those shown.

HANDLING AND PREPARATION OF LIQUID FUEL FOR BURNING

Oil is brought to the user by rail tank car, road tank wagon or barge as well as by coastal tankers, and is then discharged by pipeline into the main storage tank. In this operation care is needed to avoid spilling; correct equipment and supervision are essential.

All oils may contain a very small amount of water—usually less than 0.1 per cent. in distillate oils; this may settle in storage and must be removed at regular intervals. When present in oil lines, water may cause the flame to be unstable, or may even extinguish it.

In most petroleum fuels, particularly if heated, the water settles to the bottom of the tank and should be run off through a drain cock fitted at the lowest point. This should be of the *lock shield* type. In tar oil fuels, however, the water will normally collect on the surface and must be removed by an appropriate water draw-off arrangement. Water may also be found in oil filters, which should be cleaned periodically.

The heavier liquid fuels require heating (a) for ease of pumping and (b) especially for ensuring that they have the correct viscosity at the burner.

Heating is usually done in two stages:

1. In the main storage tanks.

The oil is here raised to a temperature that will ensure an adequate flow to the pumps, service tanks, etc.

2. Before reaching the burners.
The oil is raised to a higher temperature, and thus acquires a sufficiently low viscosity to ensure good atomization by the burner.

The amount of heat required in Stage 1 depends upon the grade of the oil, the size, arrangement and exposure of the storage tanks and pipework, and the general lay-out of the plant. The temperature required in Stage 2 depends mainly upon the type of burner and the application. The grades described in Table 1 above should be heated to the temperatures shown in Table 2.

TABLE 2
STORAGE AND ATOMIZATION TEMPERATURES REQUIRED
FOR VARIOUS OILS

Grade and B.S. class	for storage	for atomization
Gas oil: A	No pre-heat necessary.	Atmospheric is normally sufficient
Light or Medium fuel oil: E ..	45° F.	120–140° F.
Heavy fuel oil: F	80° F.	175–200° F.
Extra heavy fuel oil: G	100° F.	250° F.

Oil Pipelines

The sizes of pipelines can be calculated as described in Chapter 10. For the heavier grades of oil the bore of the pipe should be not less than 1 in. When possible, oil lines should be placed in a warm position, free from draughts. Alternatively, they may be placed under the floor in trenches covered by protective plating. Hot oil lines should be lagged and may need heating by electric or steam *tracer lines*.

FUEL SYSTEMS

Three systems are commonly used for supplying liquid fuels to furnaces.

1. Gravity feed system.

When only one or two burners are involved, a simple gravity feed system may be adequate. This comprises either an overhead storage tank to which deliveries can be made, or a ground level storage tank with a transfer pump delivering to a gravity feed service tank. From either the service tank or the overhead storage tank a single feed line is run to the burners. Such an installation is illustrated in Fig. 2.

2. Circulating ring main system with fuel at atomizing temperature.

This system comprises a storage tank or tanks to which the liquid fuel is delivered, followed by a pump, filter and flow heater, which in most cases should be duplicated. The ring main takes the fuel at atomizing temperature from the heaters and circulates it round the factory. The return leg of the ring main is normally led back to the pump suction and not to the storage tank. This is done to minimise the consumption of electricity or of steam for the necessary heating, since it is common practice to circulate two or three times the quantity of liquid fuel actually used for burning. Ring mains should be arranged so that the branch lines to the burners are as short as possible.

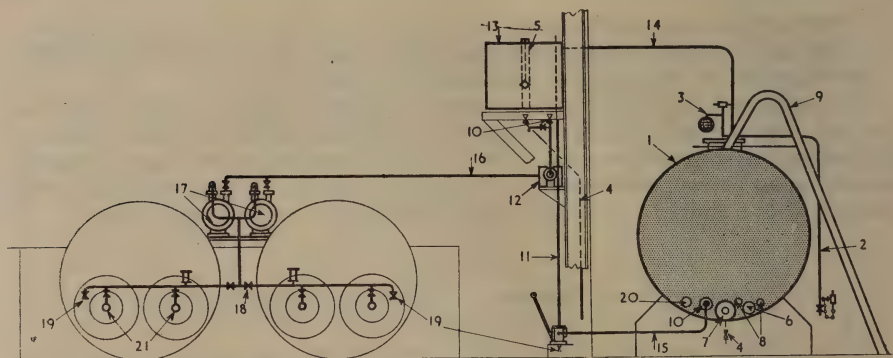


FIG. 2. Gravity feed oil storage installation supplying two Lancashire boilers.

- | | |
|---|--|
| 1. Main storage tank. | 12. Constant level discharge tank. |
| 2. Fill pipe. | 13. Service tank. |
| 3. Vent and dip pipe. | 14. Vent and overflow. |
| 4. Sludge valve. | 15. Suction line from storage tank. |
| 5. Oil level indicator. | 16. Feed line from service tank to line heaters. |
| 6. Electric heater. | 17. Steam line heater (thermostatically controlled). |
| 7. Steam coil (with strainer and trap). | 18. Branch line from heater to burner (lagged). |
| 8. Thermostats. | 19. Drainage point. |
| 9. Access ladder and platform. | 20. Storage tank thermometer. |
| 10. Oil outlet valve. | 21. Oil burner with metering valve control. |
| 11. Oil transfer line to service tank. | |

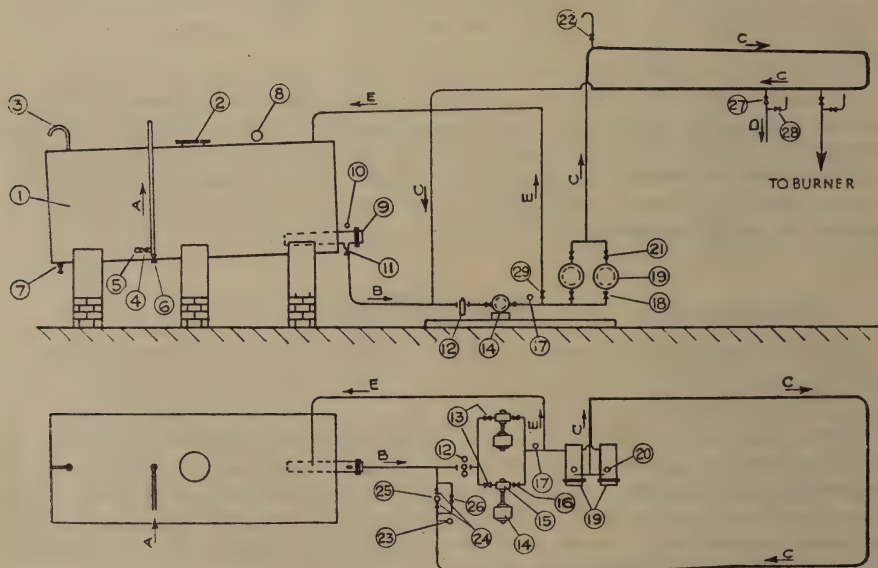


FIG. 3. Duplex ring main system.

- | | |
|---|--|
| 1. Storage tank. | 18. Fuel line heater inlet valve |
| 2. Manhole and cover. | 19. Fuel delivery line heaters, thermostatically controlled. |
| 3. Vent pipe. | 20. Thermometers. |
| 4. Filling line valve. | 21. Fuel line heater outlet valve. |
| 5. Filling line hose connection and dust cap. | 22. Ring main vent cock (fitted at highest point). |
| 6. Filling line drain cock. | 23. Thermometer. |
| 7. Drain cock. | 24. Valves for isolating stabilising valve. |
| 8. Depth gauge. | 25. Fuel pressure stabilising valve. |
| 9. Electric outflow heater, shrouded type, thermostatically controlled. | 26. Valve for bridging stabilising valve. |
| 10. Thermometer. | 27. Fuel branch line shut-off valve. |
| 11. Outlet valve. | 28. Fuel branch line vent cock. |
| 12. Fuel suction line twin strainer. | 29. Valve on fuel cleaning line back to storage tank. |
| 13. Pump inlet shut-off valves. | A Fuel tank filling line. |
| 14. Fuel pump electric motor. | B Fuel suction line. |
| 15. Fuel pumps. | C Fuel ring main. |
| 16. Pump outlet shut-off valves. | D Fuel branch lines to burners. |
| 17. Fuel delivery pressure gauge. | E Fuel cleaning line back to storage tank. |

In this system the oil may be circulated under pressure to feed pressure jet atomizers, or can operate at a nominal 10–20 lb. per sq. in. to supply burners using a separate atomizing medium. See Fig. 3.

3. *Fuel circulation at storage temperature*

This system employs a ground level storage tank in which the fuel is kept at a pumpable temperature, generally below the atomizing temperature. The fuel is circulated through pipes of relatively larger diameter, and at each furnace or group of furnaces a branch line, which should be kept as short as possible, passes the fuel to the burners through small heaters, which raise the oil temperature to that required for atomization.

All the foregoing systems are subject to modification according to the type of fuel to be burnt. Thus with light distillate oils, such as gas oil or C.T.F. 50, no heating is required, the fuel lines may in all cases be unlagged, and it is not even essential to provide drainage facilities, though they can be most useful. On the other hand, if a viscous fuel of the 950 sec. petroleum oil class, or C.T.F. 200, is to be used, storage temperature should be thermostatically controlled at 80–100° F., and the fuel pre-heated to about 170–200° F. before atomization. Pipelines should be lagged and may be heated by tracer steam line; adequate vents and drain points should be provided. With the most viscous fuels concentrically steam-jacketed pipelines, heated pumps and heated filters can be used. All these points are brought out in the illustrations to which reference has already been made.

BURNER TYPES

Liquid fuel is burned by breaking down a continuous stream of the liquid into very small particles, thus exposing a large surface area of combustible material to the effects of radiant heat from the furnace in the presence of atmospheric oxygen.

There are four types of mechanism for burning liquid fuel :

- a. those in which the fuel spray is produced by mechanical means,
- b. those in which the fuel is broken down into a spray by physical impact with an atomizing medium,
- c. a combination of spinning cup and blast,
- d. those in which the fuel is vaporized, e.g. the pot burner; this is not a type of atomizer in the ordinarily accepted sense of the term.

The various categories may be further sub-divided as follows :

Pressure jet burners ("Simplex")

Liquid fuel at the correct viscosity for atomization (100 sec. Redwood No. 1 or less) is fed into the nozzle of a pressure jet burner through a series of ports so placed that as the oil issues from the final orifice into the furnace it has acquired a high rotational speed. As the oil leaves the nozzle it breaks down into small droplets, which become a conical spray with a cone angle depending upon the two component forces, i.e. (i) forward velocity, and (ii) speed of rotation.

Depending upon the type of fuel to be atomized such simple pressure jet burners operate at pressures of upwards of 100 lb. per sq. in. Pressures up to 1,000 lb. or more are used in special techniques where intensive combustion is required. As the amount of oil delivered is a function of the square root of the pressure, the output of a given nozzle can in ordinary industrial practice be varied over only a very small range. As atomization deteriorates rapidly if the pressure is allowed to fall, the simple pressure jet is normally used for boilers with a constant load. Variations on such installations are usually met

by changing the number of burners in operation, or by changing the nozzle to one of greater or smaller orifice. Fig. 4 illustrates two different arrangements of pressure jet nozzles.

Controlled pressure jet burners ("wide range")

Considerable ingenuity has been exercised in designing pressure jet nozzles capable of wide variation in throughput without loss of efficiency. The most common type is the controlled pressure jet in which the oil in the nozzle, rotating at a high velocity in a small *swirl chamber*, either issues into the furnace as a spray or returns to a low pressure fuel return line through a pipe and control valve which bleeds the swirl chamber. This device, sometimes referred to as a *spill jet*, may be used very conveniently in a ring main layout where the outgoing leg of the ring main is at atomizing pressure and terminates in a pressure release valve from which the return side of the ring main runs back at low pressure to the pump suction. The controlled pressure jet burners are fed from the high pressure side and bled at a variable and controllable rate back to the low pressure side of the ring main.

Some types of pressure jet burners use a sliding piston to get variable output. In these cases an increase in oil pressure forces back a spring-loaded piston adjacent to the swirl chamber and exposes additional grooves feeding the burner orifice.

Rotary atomizers

Other types of mechanical atomizers break down the liquid fuel by causing it to be thrown from the edge of a disc or cup rotating at high speed. The disc, which may be driven by an electric motor, is attached to an extension of the motor shaft. The shaft is hollow and the oil is fed down the centre to enter the furnace as it is thrown off in the form of a fine spray from the edge of the disc or cup. In a similar type the cup is rotated by a small air turbine; in this case the air, after passing through a system of turbine vanes, converges on the spray, thereby providing air for combustion and probably further assisting in the atomization. (See Fig. 5.)

Burners using an external medium for atomization

These are low, medium and high pressure air atomizers and steam jet atomizers, and are generally known as *blast burners*. The burners consist essentially of two concentric tubes. The oil is allowed to flow down the central tube at atomizing temperature and at a controlled rate. The atomizing medium passes down the annulus between the two tubes, also at a controlled rate, and by the action of a convergent nozzle strikes the oil as it issues from the central pipe. Depending upon the angle of the nozzle and the viscosity of the oil, a conical spray is developed which may have an included angle of from 60° to 120° .

As atomization is a function of the kinetic energy it will be appreciated that with a blast burner using steam or air at 100 lb. per sq. in., the annular space between the inner and outer tubes at the nozzle can amount to only a few hundredths of an inch. Conversely, low pressure air burners operating at an air pressure of 1 lb. per sq. in. produced by a single-stage fan, may have air apertures at the nozzle half an inch or more wide. Medium pressure atomizers are intermediate in this respect. Figs. 6 and 7 show two makes of low pressure air burners and Fig. 8. illustrates a medium pressure air burner.

Vaporizing or Pot Burners

This type of burner is becoming familiar in portable domestic heaters, but larger sizes are used for domestic hot water supply and central heating. (see Fig. 9). These burners use paraffin (kerosine) or light petroleum distillate;

coal tar fuels are not suitable. The oil is vaporized from the surface of a small pool by the heat of the flame, and the burners are so designed that radiation to the oil surface is not excessive, though adequate to maintain the desired rate of combustion. A further feature of the design of the burner is a device to maintain the pool of oil at constant level without overflowing.

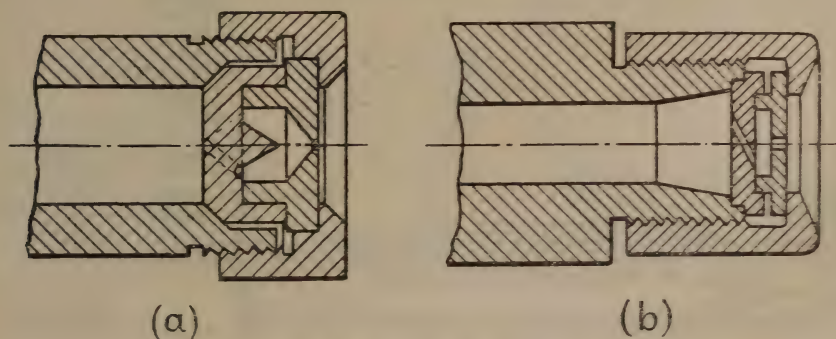


FIG. 4. Pressure jet nozzles.

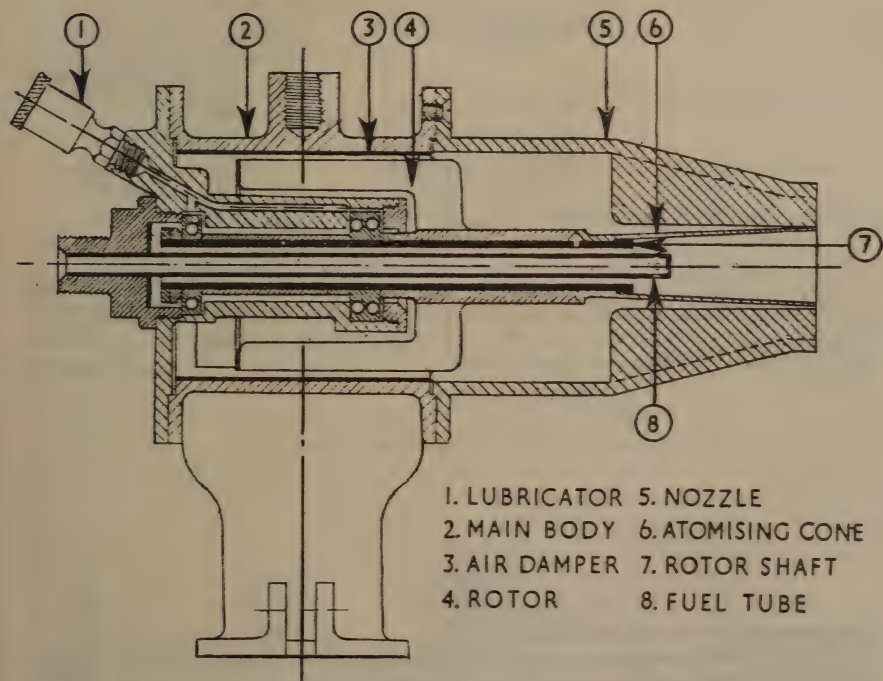


FIG. 5. Spinning cup burner.

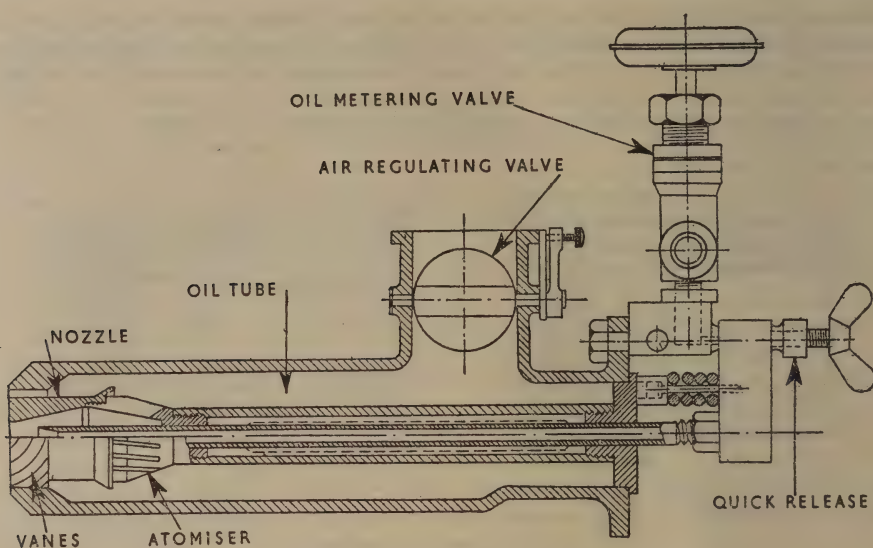


FIG. 6. Low pressure air burner.

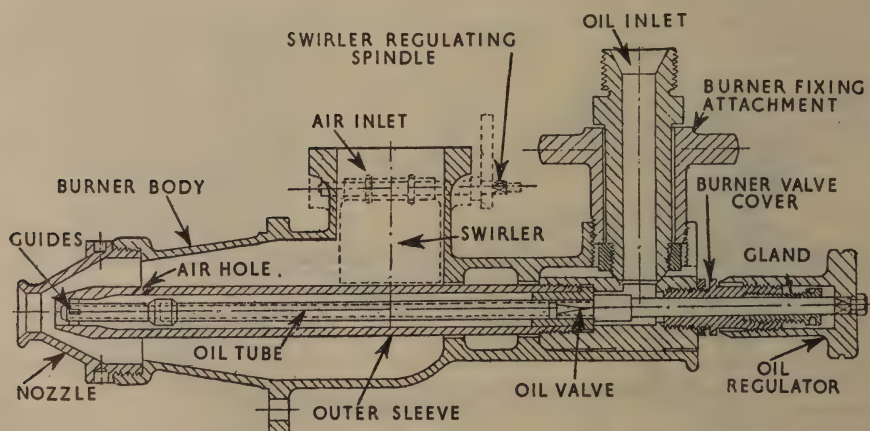


FIG. 7. Low pressure air burner.

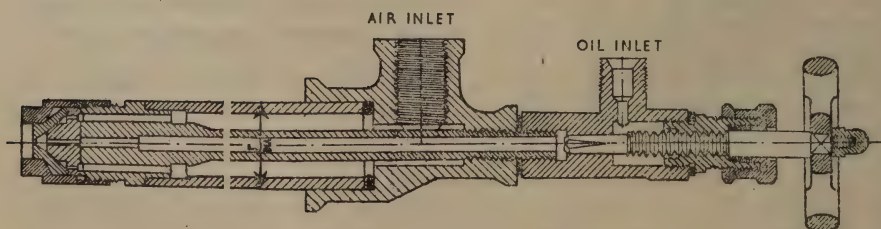


FIG. 8. Medium pressure oil burner.

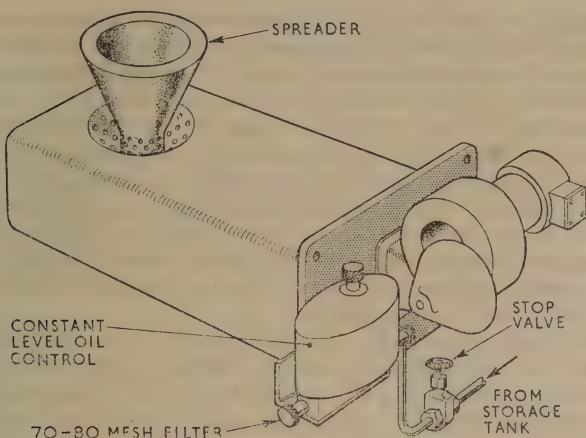


FIG. 9. Pot type vaporizing burner

THE SELECTION OF OIL BURNING EQUIPMENT

GENERAL PRINCIPLES

For any proposed installation there is a wide variety of burner types to choose from. Satisfactory operation may depend to a large extent on the selection of the correct type of burner for each individual case. To put it simply, it can be assumed that the choice lies between a pressure jet, a high pressure blast burner and a low pressure blast burner. The choice usually depends upon four main factors :

1. the range over which the burner will be expected to operate, i.e. the rate of maximum to minimum fuel consumption, (sometimes called "turn-down range");
2. the temperature conditions in the combustion chamber;
3. the shape of the combustion chamber;
4. the required combustion intensity, as expressed in pounds of fuel burned per hour per unit volume of combustion chamber.

1. *Range over which the burner will be expected to operate*

For many industries the boiler load will be sufficiently stable to warrant the selection of pressure jet equipment but in certain industries, such as laundries (where sharp and appreciable changes in load frequency occur) the blast burner may, for reasons indicated below, be a better choice.

The pressure jet nozzle if divorced from its air register will only produce a shapeless cloud of droplets, the heavier of which soon sink to the ground. It is the dual function of the air register to ensure mixing of oil droplets and air and to mould them into a flame of the desired shape. For this, a minimum air velocity of perhaps 50 ft./sec. is needed. The production of a wide range pressure jet atomizer demands the production of a wide range air register. Unless this can be done, in order to preserve a minimum speed of 50 ft./sec. at low output, much higher speeds and hence higher pressure drops across the air register are required at the upper end of the burner range. Some manufacturers have accomplished this. In contrast the blast burner will usually produce a suitable flame even where the combustion air is brought in at low velocity.

2. *Temperature conditions in the combustion chamber.*

If a process involves a high combustion temperature, which can be obtained

only by burning the fuel with highly pre-heated air, there is a limit to the temperature to which the air to be passed through the burner can be safely pre-heated; in such cases arrangements must be made to take the greater part of the hot air direct to the combustion chamber. Hence the amount of cold air passing through the burner must be kept to a minimum and for this type of application the high pressure air or steam atomizing blast burner is the correct choice. For such applications the quality of atomization may be relatively unimportant and coarse atomization may in certain cases be tolerated if it is required to extend the flame down a very hot combustion chamber. For very high temperature furnaces the burner mainly serves the purpose of an injector of fuel, the temperature of the environment itself ensuring that the fuel will ignite and burn completely.

In contrast some chambers are much colder than the flame, a typical example being the flame tube of a shell boiler. In spite of the high rate of heat transfer from the flame, the walls remain at a temperature virtually that of the water in the boiler. The high rate of heat transfer from flame to cold wall results in a rapid cooling of the flame so that the combustion must be quick and complete, i.e. atomization must be good, and air and oil droplet mixing very efficient.

3. *Shape of the combustion chamber.*

It is comparatively easy to design a blast burner to give any flame shape desired from the long and narrow with an included angle of (say) 20° to a very wide sunflower type of flame with an included angle of 180° . The wider the flame the easier it usually is to introduce the air among the oil droplets and effect good mixing. With long thin narrow flames the atomizing air and the air sucked into the root of the flame by the injector action are together usually sufficient to initiate combustion, the remainder of the air being gradually sucked into the flame as combustion proceeds. In the case of pressure jet atomizers, the spray angle is to a large extent associated with quality of atomization and it is difficult to obtain a narrow-angle spray from a pressure jet atomizer without coarsening the quality of atomization.

Where burners of the pressure jet types are selected for small diameter flame tubes it is necessary to use the momentum of the incoming combustion air to bend the natural trajectory of the oil drops and so mould the flame to a narrower shape. For such propositions, if a pressure jet is selected rather than a blast burner it should be supplied with a forced draught casing so as to ensure a reasonable air velocity through the air register and brick quarl, the latter playing a very important part in promoting good mixing and flame stabilization.

4. *Required combustion intensity*

In sectional boilers the combustion intensity may be as low as $1\frac{1}{2}$ lb./cu. ft. hr. For furnaces, the intensity may be 5–10 lb./cu. ft. hr. For certain specialized applications, considerably higher combustion intensities, up to 70 lb./cu. ft. hr. have been used.

To obtain a high rate of heat release, the combustion process must be expedited; this is achieved by fine atomization and high momentum of the combustion air. High combustion intensity is, therefore, obtained at the expense of auxiliary power. In certain cases high combustion intensity results in an improvement in efficiency which outweighs the loss equivalent to the auxiliary power used. In large water-tube boilers it may be essential to complete the combustion of one or two tons per hour per burner within a distance of 18 to 25 feet. Where pressure jet burners are used, the problem has been solved by employing fuel atomizing pressures up to 1,000 lb./sq. in.

and combustion air pressure, in the windbox, of 8 in. g. The high intensity combustion associated with the gas turbine may call for even higher pressure drops across the air registers.

PRACTICAL ASPECTS

In ordinary practice the simple pressure jet can operate satisfactorily over variations of output of the order of 25 per cent. Wide range pressure jet burners, rotary atomizers and burners using steam or compressed air may have turn-down ratios as high as 5:1.

The main application of the pressure jet burner is to boilers, and (more recently) to gas turbines. It is not normally used for high temperature furnace work because of a tendency to foul if overheated.

The pressure jet atomizer may be used for all commercially available grades of liquid fuels, except the most viscous varieties of coal tar fuels. Using distillate liquid fuels, one can burn 1 gal. per hour or less, but with such low outputs at 100 lb./sq. in. atomizing pressure the final orifice and swirl grooves may be as small as 0.007 in.; hence very special filtering precautions are necessary to prevent choking. The more viscous liquid fuels may be used at a minimum rate of some 5 to 10 gal. an hour, and 950 sec. petroleum oil or C.T.F. 200 may be atomized very successfully at these rates. Pressure jet burners have the advantage of being silent in operation, they are simple to install, and the power needed to keep the oil at its atomizing pressure is appreciably less than that used in indirectly atomized systems.

Low and intermediate pressure air atomizers using a single-stage fan or a simple form of blower to provide the necessary air are most common in the metallurgical industries and are now becoming popular for boiler firing. The low pressure air burner is used in drop forging furnaces, small crucible furnaces, billet heating furnaces and bar and strip furnaces. The medium pressure air burner is used in glass tank heating and continuous tunnel kiln work. These types of burners may use any grade of liquid fuel.

A high pressure atomizer generally uses steam rather than compressed air. The burners have two quite distinct uses. The first of these is in boiler work where, largely as a matter of convenience, boiler steam is used to atomize the fuel. The use of steam has advantages when burning heavy residual fuels as it helps to maintain a steady flow of fuel. On the other hand, steam atomization—which uses some 2–2½ per cent. of the boiler steam—is more expensive than pressure jet atomization. The other main use for the blast burner (and here also it is generally steam that is used) is in large furnaces, particularly the open hearth furnace. In this application, burners are rated at *tons of fuel per hour per burner*, and the flames can be 50–60 ft. long. A high velocity flame is required, and it has been demonstrated by the recent work of the Flame Radiation Research Association that nozzle momentum in steam jet atomization can be a controlling factor in efficiency and speed of melting. High nozzle momentum encourages rapid mixing with combustion air while at the same time maintaining flame length. On the other hand, for large cement kilns, special narrow-angled pressure jets are commonly used.

Another use for the steam jet atomizer is the firing of locomotive boilers, where the simplicity and advantages of the system are specially important.

DRIP FEED SYSTEMS

The drip feed system is applicable only where the chamber in which the oil is to be burned is at a temperature above 600° C. It is very simple and cheap since the only apparatus required is a valve to control the rate of oil flow and a suitably shaped piece of metallic tubing from which oil is allowed

to drip into the hot environment. It is particularly suitable for kilns of the continuous chamber type used in the brick and tile industry, since the oil drips can be introduced through the pot holes in the roof normally used for dropping coal into the kiln. Air for combustion is supplied *via* chambers already fired that are being cooled: as a result, this air becomes appreciably pre-heated. The oil droplets ignite while falling through the chamber, crossing the main air flow. In many Continental kilns deflector walls ensure that the falling drops meet rising air. Some systems employ metered intermittent fuel dosage but where continuous gravity feed is used constant fuel viscosity and pressure must be maintained.

PRODUCTS OF COMBUSTION OF LIQUID FUELS

Liquid fuels, being composed mainly of carbon and hydrogen, yield on combustion carbon dioxide and water vapour, accompanied by the nitrogen of the combustion air and also by any excess air that has been supplied. For petroleum oils, the theoretical amount of carbon dioxide present in the dry waste gases resulting from the combustion is generally between 15 and 16 per cent., and that from coal tar fuels about 18 per cent.

Fig. 10 shows combustion data for petroleum oils and indicates the losses of heat resulting from high flue gas outlet temperatures. In practice, using commercial burners, it is not possible to burn the fuel with the exact quantity of air theoretically required and an excess of from 15 per cent. to 30 per cent. may be expected. With the higher percentage of excess air the analysis of the dry flue gas would show between 11 and 12 per cent. of CO_2 on petroleum oil or 15 to 16 per cent. on coal tar fuels as normal figures for industrial application where the maximum temperature is required in the products of combustion. There are many applications where the full combustion temperature is not desired and for these the combustion products may be deliberately diluted with extra air. This often occurs in drying operations and, of course, the percentage of CO_2 measured at the outlet from the dryer would in these circumstances be no indication of the efficiency of combustion. A preferable method is to use re-circulated products of combustion as the diluent.

PRE-HEATING COMBUSTION AIR

It is not generally recommended that air should be passed through an oil burner at a temperature of above 500° F.; where a higher degree of pre-heat is to be used, it is advisable to pass a small proportion of the total combustion air through the burner for atomizing purposes, at a comparatively low temperature, and the remainder as high-temperature air through secondary air ports.

The advantages of using pre-heated air for combustion are dealt with in Chapter 8. For present purposes these advantages may be summarized thus:

- (a) the flame temperature is raised, resulting in increased heat transfer;
- (b) the speed of combustion is increased, thus further raising the flame temperature;
- (c) the amount of excess air necessary for combustion can be reduced;
- (d) the heat abstracted from the flue gases by the combustion air is returned to the furnace;
- (e) the ultimate loss is reduced.

The approximate savings in oil fuel that can be made by pre-heating the air are shown in Table 3.¹

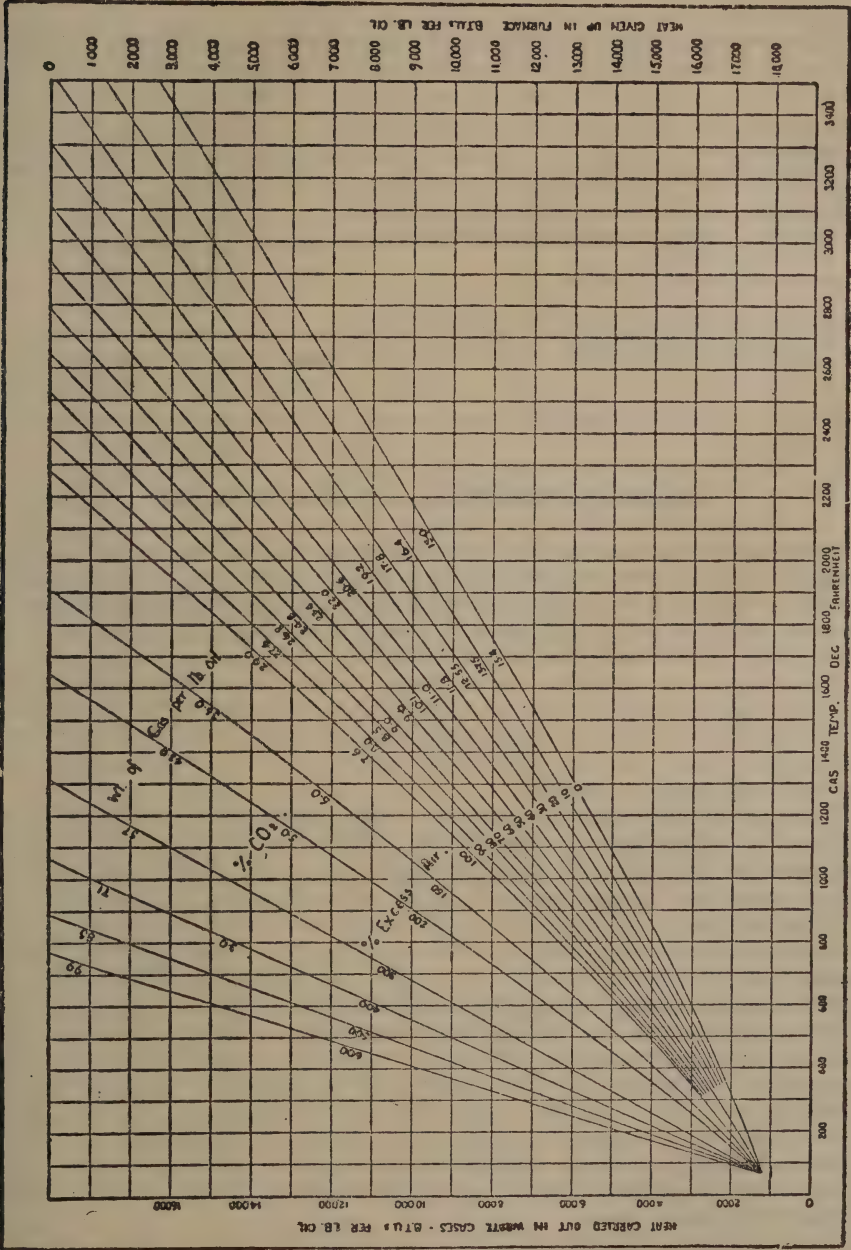


FIG. 10. Combustion data for petroleum oils.

(Reproduced, by permission, from "The Science of Petroleum," vol. IV, by F. J. Battershill, I. Lubbock and R. H. B. Foster; Oxford University Press.,

TABLE 3

Approximate savings in oil consumption using pre-heated air, calculated on a basis of 20 per cent. excess air for combustion and a flue gas temperature of 800° C. (1,470° F.):

Passing all combustion air through burners at a temperature of	200° F.	300° F.	400° F.	500° F.
Approximate saving in fuel per cent.	4.8	7.9	10.9	13.7
Passing 25 per cent. of combustion air at 200° F. through burners and remainder as secondary air at a temperature of	700° F.	800° F.	900° F.	
Approximate saving in fuel per cent.	15.9	17.8	19.7	
Passing 5 per cent. of combustion air cold through burner and remainder as secondary air at a temperature of	700° F.	800° F.	900° F.	
Approximate saving of fuel per cent	18.2	20.5	22.7	

BURNER OPERATION AND MAINTENANCE

When operating pressure jet burners, the size of the burner nozzle, the oil pressure and the temperature should all be in accordance with the maker's recommendation. The burner manufacturers calibrate *nozzle capacity* against *pressure* with fuel oil at a given viscosity. From these calibration curves the correct size of the nozzle can be determined.

The temperature to which the oil should be heated to obtain the required viscosity can be read off from the temperature/viscosity curve. It should be noted that oils of different origin may have somewhat different curves, hence even if they have the same viscosity at say 100° F. their viscosities at other temperatures may be different.

Duplicate oil filters are generally provided, at the inlets to the fuel pump and at the outlets from the fuel heaters. Water may collect at these points, and must be removed periodically through drain cocks. The burner operation can be upset by particles lodging in the small passages of the nozzles and equally, of course, by clogging of the filters; both need regular and careful cleaning. Filters of the Duplex or self-cleaning type make cleaning possible without stopping the plant. Pressure gauges are commonly fitted before and after filters, to indicate by pressure differences when cleaning is necessary.

On marine boilers, where heavier oils are generally burned, it is usual practice to change burners at intervals of four to eight hours, so that any carbon deposit on the nozzles may be removed. When the nozzle is dismantled, the burner is soaked in kerosine or gas oil to facilitate cleaning. Creosote is used to clean burners handling coal tar fuels. On no account should any tool be used that might enlarge or damage the sharp clean edges of the final orifice or the small oil passages when cleaning parts of the nozzle, as even a barely visible scratch can ruin it.

When lighting a burner the air supply must first be established and then care must be taken to ensure that a flame from a torch or other source is placed in front of the nozzle before turning on the oil supply to the burner. It is also necessary to ensure, before applying the lighting-up torch, that there is no oil vapour in the combustion chamber that would be likely to cause a blow-back. If oil has been spilt and vaporised by the heated bricks, air should be allowed to pass through the combustion chamber for a sufficiently long "purge period" to remove the hazard.

When blast burners are used, each must incorporate some form of simple graduated indicator attached to the valve. This should show the degree to which the valve is open. With hand regulation, graduated valves enable the operator to regulate the oil flow to the burner to a predetermined amount. The air regulators should be similarly graduated so that rates of oil and air supply are correctly adjusted during periods when the load is varying.

Combustion should be controlled by flue gas analyses. The best method is to use a CO_2 recorder checked periodically by use of an Orsat apparatus. When there is no instrument for the purpose, the air supply is adjusted to the minimum that will ensure reasonably smoke-free combustion.

Maintenance of the Burner

The oil burner must be kept in good order. Maintenance depends to some extent upon the type of burner used, but most of the directions given here apply to steam jet and air jet burners.

It is important to prevent the burner from becoming over-heated. The metal is cooled to some extent during the passage of air or steam and oil through the nozzle, but when the oil is shut off, radiant heat from the furnace may over-heat the metal of the nozzle, and the fuel left in the burner may become carbonized. One widely practised method of avoiding this with steam jet burners is to keep a little steam passing through the burner during shut-down periods so long as the furnace is hot. But the practice wastes steam. The more economical method is to remove the burner as soon as the oil supply is turned off. If this should not be possible, the burners should be protected by a refractory-tile interposed between the burner nose and the furnace.

COAL TAR FUELS

It is useful to consider the comparison between the various grades of coal tar fuels described in Chapter 3, and those derived from petroleum and described in Chapter 4. Both ranges extend from light distillate oils to heavy residuals, with intermediate fuels which can be mixtures of these two extremes. Provided, therefore, that the appropriate grade of coal tar fuel is selected, it can in most cases be used in direct substitution of petroleum fuel, at least in so far as equipment is concerned. It is impracticable to mix the heavier grades of coal tar fuels with the petroleum oil fuels because of a mutual precipitation of gelatinous bituminous matter. Changes from one class of fuel to the other should, therefore, always be accompanied by an intermediate washing stage using a light grade tar oil for this purpose. Such changes must always, however, be considered with reference to the furnace, because the mechanism of combustion of the "aromatic" coal tar fuels is quite different from that of the (mainly paraffinic) petroleum oil fuels. The carbon/hydrogen ratio is very much higher than that of the petroleum oils and in the earlier stages of combustion a considerable proportion of the carbon is liberated as carbon particles within the flame. Although petroleum oil fuels also produce carbon particles in the flame, combustion of these fuels more nearly approaches an intermediate vaporization state. In consequence, particular attention must be paid to adequate mixing of combustion air when burning coal tar fuels, to prevent carbon growth on the walls if the furnace is of restricted dimensions. For the same reasons, coal tar fuels cannot be used with any type of vaporizing or pot burner.

Table 4 gives the relevant data for these fuels.

TABLE 4
COAL TAR FUELS:
STORAGE AND ATOMIZING TEMPERATURES

<i>Fuel</i>				<i>Storage temperature</i>	<i>Atomizing temperature</i>
				° F	° F
C.T.F. 50	..	..	..	Atmospheric	40- 60
C.T.F. 100	..	..	..	90	90-100
C.T.F. 200	..	..	..	80-100	170-200
C.T.F. 250	..	..	..	140-160	230-250
C.T.F. 300	..	..	..	160-200	270-300
C.T.F. 400	..	..	..	250-300	360-410

C.T.F. 50, and C.T.F. 100, which are distillate oils, may be used as alternatives to the distillate petroleum oils. C.T.F. 50 requires little or no pre-heating for atomization. C.T.F. 100 must be stored at about 90° F. and atomized at between 90-100° F.

C.T.F. 200 can in general replace 950 sec. petroleum oil; both are mixtures of distillate and residual materials and both require the same storage and atomizing temperatures.

The heavier coal tar fuels, C.T.F. 250, C.T.F. 300 and C.T.F. 400, require special techniques similar to those of the burning of very heavy petroleum fuels. These techniques are based largely upon the fact that the fuels are either very viscous or solid at atmospheric temperatures. Precautions have, therefore, to be taken to store the fuels at temperatures ensuring adequate fluidity for pumping. Heaters must also be provided between storage and consuming points to raise the temperature and thereby lower the viscosity of the fuel for atomization.

Except for the lightest distillate oils, fuel circulating lines, pumps and filters must be heated either by steam or by electrical tracer lines to prevent serious temperature loss during use. All such systems for viscous fuels must be lagged. In extreme cases, steam jacketing may have to be used. With the more viscous liquid fuels provision must be made for draining burning systems when shutting down.

Sulphur Content of Coal Tar Fuels.

Although the sulphur content of all coal tar fuels is substantially less than that of corresponding petroleum oils, some supplies may occasionally contain a trace of sulphuretted hydrogen. For this reason it is better, with new installations, to select equipment made from ferrous metals rather than from non-ferrous metals such as brass and copper. If these latter are already installed, it may be found that nothing more than a slight blackening of the surface takes place over years of use with coal tar fuels, but on the other hand thin sections such as gauze filter baskets, and pressure regulating diaphragms, may be sufficiently attacked to put them out of action.

Other Aspects of Coal Tar Fuels

The coal tar fuels are very much more powerful solvents than the petroleum oils. For this reason, joints in pipework and other equipment are best made with plain asbestos millboard. Rubberized asbestos compounds are not suitable.

Comment upon various types of burners and burner systems is made earlier in this Chapter. It is usual with heavy grades of liquid fuel such as C.T.F. 300 and C.T.F. 400 to use steam jet atomization, whereas with the lighter grades

all normal types of burners may be used. It should be noted that with pressure jet application of C.T.F. 200 the spray cone established within the furnace requires either forced or induced draught for adequate mixing, and combustion without smoke. Natural draught of the usual order of $\frac{3}{8}$ in. to $\frac{3}{4}$ in. is not generally adequate in these circumstances; $1\frac{1}{2}$ in. to 2 in. W.G. is preferred.

Amount of Air Required for Combustion of Coal Tar Fuels

The amount of air theoretically required to burn 1 lb. of coal tar fuel is of the order of 160 cu. ft. at N.T.P., but in designing plant it is customary to base calculations on a figure of 200 cu. ft. of air per lb.

MINERAL MATTER AND ASH IN PETROLEUM OIL FUELS

Liquid fuels rarely contain as much as 0.25 per cent of mineral matter (ash) and the amount is generally below 0.1 per cent. Nevertheless, such incombustible mineral matter as may be present may present problems in use. Apart from such obvious hazards as rust from tanks and pipe-lines, and of course water (to which reference has been made at the beginning of this chapter) other inorganic constituents have attracted notice. An example may be quoted of an oil that contained 0.05 per cent. of "ash," and this ash included 65 per cent. of vanadium (as oxide, V_2O_5), 2.5 per cent. of alkali oxides (as Na_2O) and 9 per cent. of nickel (as NiO). Hughes and Voysey² quote an ash content of 0.044 per cent. which had 62 per cent. of V_2O_5 and 4.7 per cent. of NiO . When used as a gas turbine fuel this oil gave deposits on the blades consisting (as the limits of several runs) of 4 to 4.8 per cent. Fe_2O_3 , 15 to 17 per cent. of NiO , 33 to 45 per cent. of V_2O_5 , 15 per cent. of Na_2O and 17 per cent. of SO_3 . Vanadium occurs as an organic vanadium compound of high molecular weight containing about 5 per cent. of vanadium; it is thus not possible to remove it. It appears that some oils contain only traces of vanadium but it is a constituent of most oils.

The deposition of fuel oil ash containing alkalies and vanadium seems to be following the same course as that of normal ash deposits in water-tube boilers (see pages 264-5).

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STEAM BOILERS

CHAPTER 14

WITHIN the limits of modern knowledge, steam forms the most convenient and the most economical vehicle of heat for power and process purposes. Other substances, for example, mercury and diphenyl, have been used in place of water, but none of these is so universally available as water. Steam boilers, therefore, predominate in industry, and range in size from the elementary unit evaporating a few gallons an hour to the complicated power-station steam generator with an output of many thousands of pounds of steam an hour.

The purpose of a steam boiler, more correctly a steam generator, is to produce steam under pressure from the raw materials fuel, air and water. The potential heat of the fuel is made available by the process of combustion (see Chapter 7) and this available heat is transmitted to and stored by water vapour in the form of sensible and latent heat.

The change and transference should be made with the minimum loss of heat, i.e. at maximum efficiency, always bearing in mind financial as well as practical limitations. Given equally efficient firing conditions, therefore, a good average thermal efficiency must be inherent in the design of a boiler by virtue of the disposition and form of its heating surfaces. Higher efficiencies are generally obtained, particularly for operating at high temperatures and pressures in water-tube boilers, by incorporating air heaters, economisers, etc., as integral parts of the complete steam generating unit.

Equivalent Evaporation "from and at 212° F."

Since the total heat in steam depends upon the pressure and the temperature of the steam, an expression stating the evaporation of a boiler simply in terms of *pounds of water per hour* is insufficiently informative unless the pressure and temperature are also specified. Accordingly, in the expression commonly used, the boiler is assumed to generate steam at atmospheric pressure (14.7 lb./sq. in. abs.) from water at 212° F. to steam at 212° F., i.e. to supply the latent heat of steam at that temperature.

The expression thus becomes:

Equivalent evaporation from and at 212° F.

$$= \frac{\text{Wt. of water evaporated} \times (\text{total heat of steam as supplied by boiler, minus heat in feed water})}{\text{latent heat of steam at 212° F. (at 14.7 lb./sq. in. abs.)}}$$

Example: If the steam is supplied at 100 lb./sq. in. abs., feed water temperature is 120° F. and the measured evaporation is 6 lb. of water per lb. of coal:

$$\text{Equiv. evap. from and at 212° F.} = \frac{6 \times (1,188.2 - 88.0)}{970.3} = 6.8 \text{ lb.}$$

The expression "from and at 212° F." is commonly written "f. and a. 212° F."

BOILER DESIGN

The development of steam boilers has in the past been based primarily on practical experience. Today, however, accumulated knowledge enables the boiler manufacturer to design with confidence and to forecast with reasonable accuracy the performance that may be expected.

The considerable advance that has been made in recent years in the design and operation of furnaces and stokers for horizontal shell boilers calls for special mention. These have undoubtedly contributed to the high efficiencies reached, enabling coals of a very wide range—both as to quality and grade—to be used in them. Mechanical stokers have also greatly simplified the problem of firing large boilers of this type.

Shell boilers are very easily adapted for oil firing, and many are installed for space heating of institutions, large buildings and workshops, the boilers being used for generating hot water at high or low pressure, or steam; some are heated by gas or electricity.

When individual boiler outputs of 2,500 to 30,000 lb. of steam an hour are required, the Economic or Lancashire boiler is widely used. In large capacity industrial and power-station installations where high working pressures are required, the water-tube boiler is necessarily adopted.

The development of pulverized fuel firing and, more recently, of the cyclone furnace (see Chapter 12) has facilitated the design of water-tube boilers to provide output capacities of several million pounds of steam an hour, to meet the requirements of modern power stations.

VERTICAL CROSS-TUBE BOILER PROPORTIONS

In a vertical cross-tube boiler similar to that illustrated in Fig. 1 the diameter of the boiler is directly related to the area of grate required to burn a given amount of fuel. Boilers of this class are normally coal-fired under natural draught, and can burn from 14 to 20 lb. of coal per hour per square foot of grate area. 1 lb. of coal of C.V. approx. 12,500 B.t.u./lb. burned in one of these boilers will evaporate from 5 to $6\frac{1}{2}$ lb. of water *f. and a.* 212° F. so that the computation of fire-grate area for a given evaporation is a comparatively simple matter.

As an example—and the method applies equally to all internally fired boilers, with suitable modifications—there is here considered a vertical cross-tube boiler required to produce about 1,700 lb. of steam per hour (*f. and a.* 212° F.). It is assumed that 18 lb. of coal are burned per square foot of grate area, and that each pound of coal will evaporate 6 lb. of water.

The evaporation per square foot of grate area will be 6×18 , i.e. 108 lb., and the grate area required will be $1,700/108$, i.e. 15.75, say 15.8 square feet. This gives a grate diameter of 54 inches and, allowing, say, $\frac{1}{2}$ inch for the firebox plate thickness, the external diameter of the firebox is 55 inches. A space of at least $2\frac{1}{2}$ inches must be allowed between the firebox and shell for cleaning and circulation, so that the shell diameter must be 60 inches.

The number of cross-tubes fitted varies according to the diameter and height of the firebox, and where diameter of tubes and firebox permit they may be fitted in pairs. In the boiler under consideration there would be above five, each 9 inches internal diameter, and to accommodate these and allow for the firehole and 10–12 inches of water leg below the firehole, an overall firebox height (measured to the top of the crown) of about 7 feet would result.

Similarly, the uptake diameter is usually about one-quarter of the shell diameter; most makers have standard sizes. In the present example an uptake having an internal diameter of 14 inches would suffice.

HEAT TRANSMISSION IN VERTICAL CROSS-TUBE BOILERS

Study of Fig. 1 shows that the bulk of the heat transmission in a vertical cross-tube boiler must be effected by radiation. The gases from the furnace pass upwards to the chimney *via* segmental passages formed by the sides of the firebox and the cross-tubes and these passages are large in proportion to the volume of the gases passing. Consequently there is little or no turbulence, and little gas gets any opportunity of contact with the heating surface in order to give up its heat. As a result the outlet temperature of the gases and the chimney losses are high with consequent low thermal efficiency.



FIG. 1. Vertical cross-tube boiler.

Boilers of this class have the important advantage that they occupy little floor space and do not need elaborate foundations. Their popularity in Britain may be attributed to these characteristics and to their ability to operate with considerable latitude in respect of quality of feed water and fuel used. They are used, for example, as crane boilers. They should be lagged and there should be a regulating damper operated from ground level.

VERTICAL FIRE-TUBE BOILERS

The vertical cross-tube boiler is not the most efficient steam generator, and when outputs exceeding 2,500 lb. per hour are required a boiler having a greater proportion of tubular convective heating surface should be used. This is to be found in the vertical fire-tube boiler which is built as two main types.

Fig. 2 shows a fire-tube boiler with vertical tubes. This is, in effect, a plain vertical boiler with a shortened cylindrical firebox, the crown of which is perforated to take the tubes. The firebox height varies from 0.75 to 1 diameter to ensure good combustion, and the sides and crown absorb the radiant heat of the burning fuel.

The products of combustion, instead of having an almost unrestricted flow out of the boiler as in the vertical cross-tube type, are split up into a number of small gas streams which give up their heat to the tube surface in passing through the water and steam spaces of the boiler. Increased efficiency results,

and as a rule the vertical fire-tube boiler has a slightly greater evaporative capacity than a cross-tube boiler of the same overall dimensions.

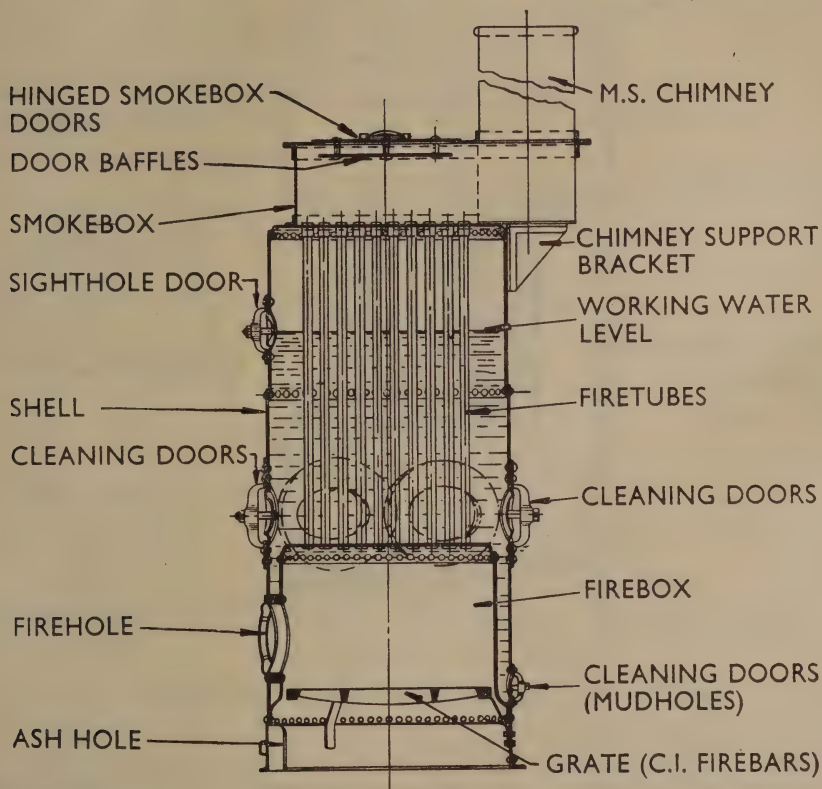


FIG. 2. Vertical fire-tube boiler with vertical tubes.

With this type of boiler there is generally a good deal of corrosion of the tubes about the water line, and there is a liability to trouble at the furnace crown owing to scale formation.

Fig. 3 shows the other basic type of vertical boiler with horizontal fire tubes. The hemispherical firebox is admirably constructed for radiant heat absorption and considerable area in the form of small diameter tubes is provided for the absorption of heat by convection. It has the additional important operating advantage that no seams or tube ends are exposed to the direct heat of the fire. Further, the refractory-lined chamber arranged in way of the back tube plate serves to complete the combustion process.

This boiler can be used for capacities up to 6,000 lb. of steam per hour under easy steaming conditions. In all but the smallest sizes it is completely accessible for inspection and cleaning on the water side.

Another design of this type has an entirely submerged combustion chamber, thus giving more radiant heat absorbing surface.

The ratio of heating surface to grate area in the form of fire-tube boiler just described varies from 10 : 1 to 26 : 1 against the cross-tube boiler ratio of 8 : 1 or 10 : 1 and higher combustion rates up to 25 lb. of coal per square foot of grate area are permissible.

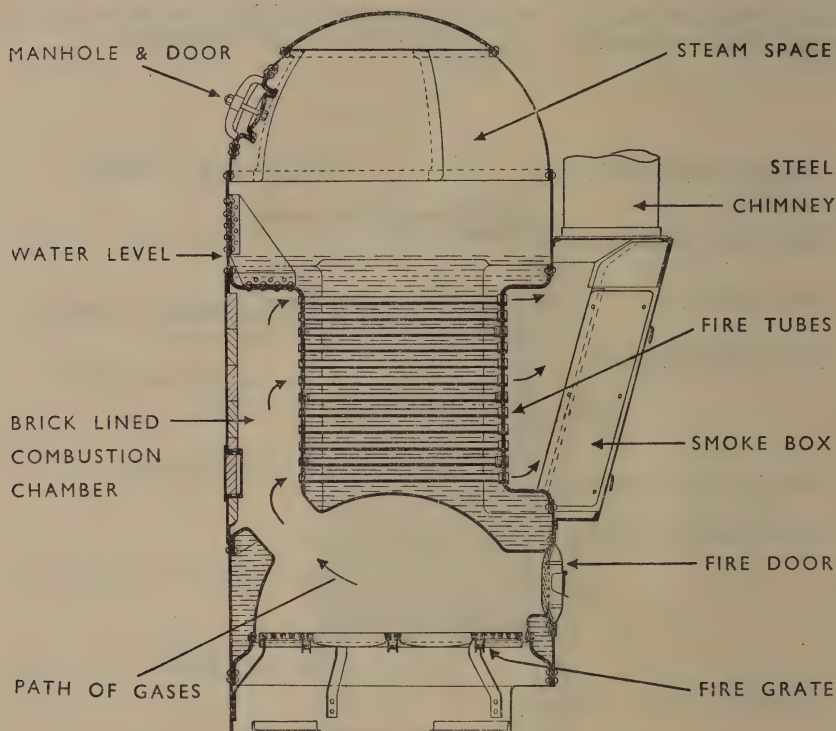


FIG. 3. Vertical fire-tube boiler with horizontal tubes.

VERTICAL WATER-TUBE BOILERS

A type of vertical boiler with horizontal water-tubes is shown in Fig. 4, the cylindrical vertical firebox being modified to form tube plates for the water-tubes. The lower parts of the firebox and the lower tube rows are subjected to the radiant heat of the fire, while the staggered nest of tubes in the upper part of the firebox is effectively scrubbed during the passage of the gases to the conventional type of uptake.

The water-tubes are given a slight inclination to the horizontal assisting in giving a positive circulation of water through the boiler. Steam-raising, in consequence, is fairly rapid, and this type of boiler is obtainable for outputs up to 6,000 lb. an hour.

This type of boiler is suitable for giving high rates of evaporation especially when the available installation space is limited. Designs involving the fitting of large doors, to give access for tube cleaning, also permit of ready inspection of the firebox.

LOCOMOTIVE TYPE BOILERS ("LOCO TYPE")

This type of boiler is used for outputs between 2,000 and 9,000 lb. an hour, the lower limit being determined by considerations of internal cleaning and inspection facilities which become rather restricted if the diameter of the barrel is much less than 3 feet 6 inches.

The Loco Type Boiler does not require any elaborate foundations, and is practically self-contained, as can be seen in Fig. 5.

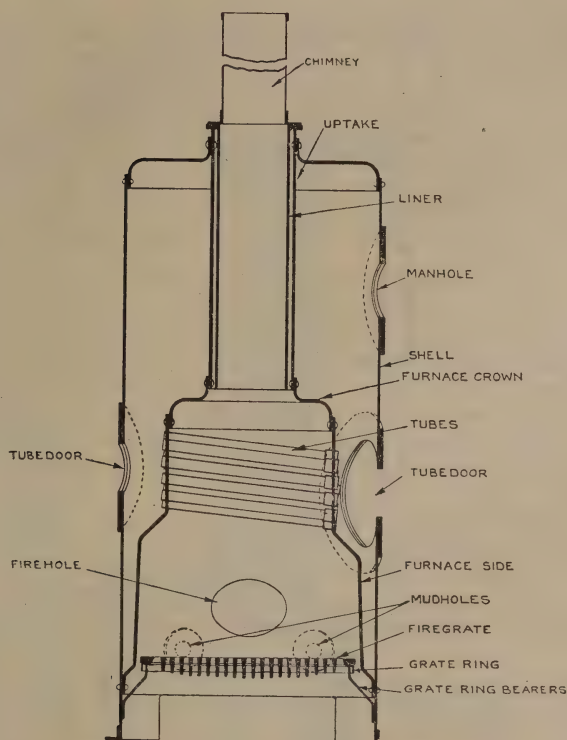


FIG. 4. Vertical water-tube boiler with horizontal tubes.

Another advantage is that, as it can be designed to incorporate a comparatively large area of heating surface, it is a fairly rapid steam generator and will stand forcing within limits.

The cubical firebox is water cooled at its sides and top, a construction giving high total heat-release figures, but having the disadvantage of poor water circulation in the surrounding water legs.

The horizontal dimensions of the firebox are dictated by the burning rate (per square foot of grate area) but the height is a compromise between the requirements of adequate combustion space, the area required for the tube plate (which, of course, also affects the barrel diameter) and the steam space required above the working water level if priming is to be avoided when steaming.

Burning rates vary between 16 and 25 lb. of coal per square foot of grate area under natural draught, and from 7–8 lb. of water can be evaporated per lb. of fuel burned.

These rates are, of course, very much less than those obtained in locomotive practice, which sometimes reach 100 lb. per square foot as a result of the induced draught effect obtained from the engine exhaust and a better circulation of the water resulting from vibration. The firebox height is limited in a boiler of this type because of its encroachment on the steam space, and also to a lesser extent because of expansion arising in service from the use of high fireboxes, thus the maximum area of boiler heating surface exposed to radiant heat is curtailed by constructional features.

The convective tubular heating surface is similarly limited in regard to cross-sectional area, but more scope is permissible with regard to length,

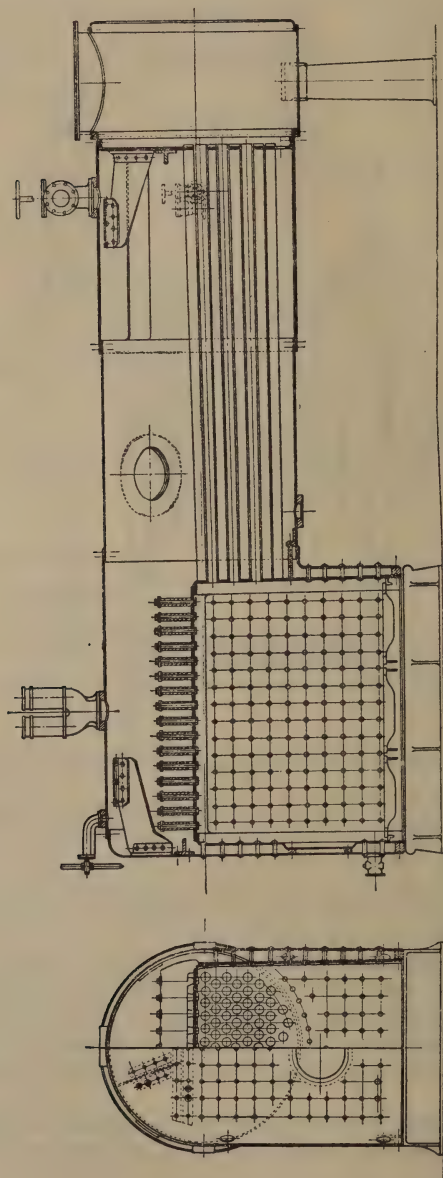


FIG. 5. Stationary locomotive boiler.

within the requirements of a reasonable draught loss. A long tube allows more opportunity for heat transmission between gas and tube wall than a short one, and a small bore tube gives better heat transmission than does one having a large cross-sectional area. Long tubes, however, may set up uneconomical draught losses, and small bore tubes are liable to become choked with soot.

The length of stationary locomotive boiler tubes is therefore between 30 and 50 diameters and the minimum external diameter $2\frac{1}{4}$ in. The ratio of total heating surface to grate area varies from 15 : 1 in the smallest, to 40 : 1 in the largest boilers.

A disadvantage of the Locomotive Boiler is that water circulation is restricted over those areas subjected to the highest temperature difference, so that a fairly pure water is required, otherwise there will be serious risk of scale formation, with consequent danger of overheating.

Boilers of this type are made for working pressures up to 350 lb. per square inch and, with modified forms of stays of the more flexible type and higher tensile plates, can be made up to 500 lb. per square inch.

CORNISH AND LANCASHIRE BOILERS

The Cornish or single-internal-flue shell boiler (shown in Fig. 6) is made for evaporative capacities ranging from 1,000 to 4,000 lb. per hour, the diameter varying from 4 feet in the smallest to 6 feet 6 inches in the largest size, with corresponding lengths of 10 feet and 24 feet respectively. It is probably used principally in the 2,000 to 4,000 lb./hr. class, since below 5 feet diameter it is somewhat cramped for inspection and cleaning purposes and the internal flue diameter becomes rather small for efficient operation. At 6 feet diameter it is possible to fit two internal flues, as in Fig. 7, and this is the smallest size of Lancashire boiler made.

The maximum size of Lancashire boiler is about 10 feet diameter; the shortest and greatest lengths being respectively 18 feet and 30–32 feet, giving an evaporative range of 3,000–12,000 lb. per hour. Cornish boilers are normally constructed for pressures up to 160 lb./sq. in., and Lancashire boilers up to 200 lb./sq. in., although there are examples of Lancashire boilers in service up to 260 lb./sq. in.

In either type of boiler the limiting factor in regard to evaporative capacity is the grate area, this being curtailed in the smallest size by the permissible diameter of flue fitted inside the shell, and in the larger sizes by the length of grate that can be properly worked by hand. In a natural draught boiler this restricts the grate area to a maximum of about 50 square feet divided between two flues, and a burning rate of 25 lb. of coal per square foot of grate area. Higher burning rates are possible by using mechanical stokers and mechanical draught, but the convective heating surface of a Lancashire boiler is such that the addition of an economiser is necessary to obtain a good overall efficiency.

The horizontal shell class of boiler has the important advantage that a reasonably maintained unit may have a useful working life of upwards of 40 years and its surfaces are readily accessible for inspection and cleaning.

HEAT TRANSMISSION IN CORNISH AND LANCASHIRE BOILERS

The ratio of heating surface to grate area is usually from 20 : 1 to 30 : 1 but 50–60 per cent. of the evaporation of a shell boiler is considered to be produced over the furnace portion, the bulk of this being effected by means of radiant heat. Assuming that the length of internal flue in which the radiant heat effect is most pronounced is approximately 15 feet, then it will be apparent that about 25 per cent. of the total heating surface provided is thus employed. The remaining 75 per cent. of the heating surface is intended to absorb the heat rejected from the furnace, but this surface must be supplemented by superheater, economiser and/or air heater heating surface if thermal efficiencies of the order of 75 per cent. or more are desired.

The internal furnace is completely water-cooled, allowing large heat-release figures per unit volume, but it has the disadvantage that any irregularity in the combustion conditions may result in heavy smoke.

The importance of the firebed surface in furthering radiant heat transmission has already been mentioned in Chapter 8, and since the transmission varies as the fourth power of the Absolute temperature, it is worth

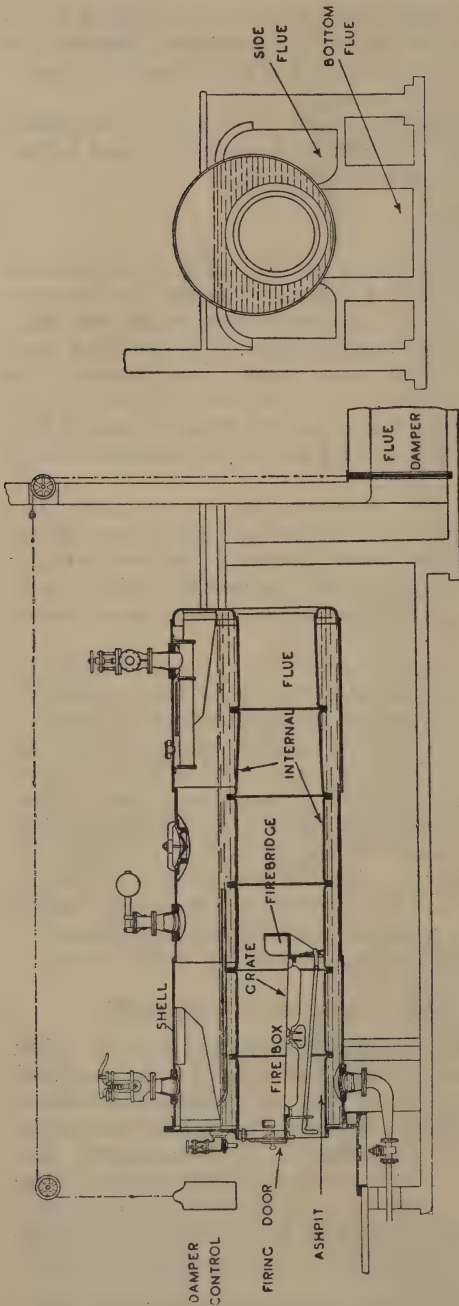


FIG. 6. Cornish boiler.

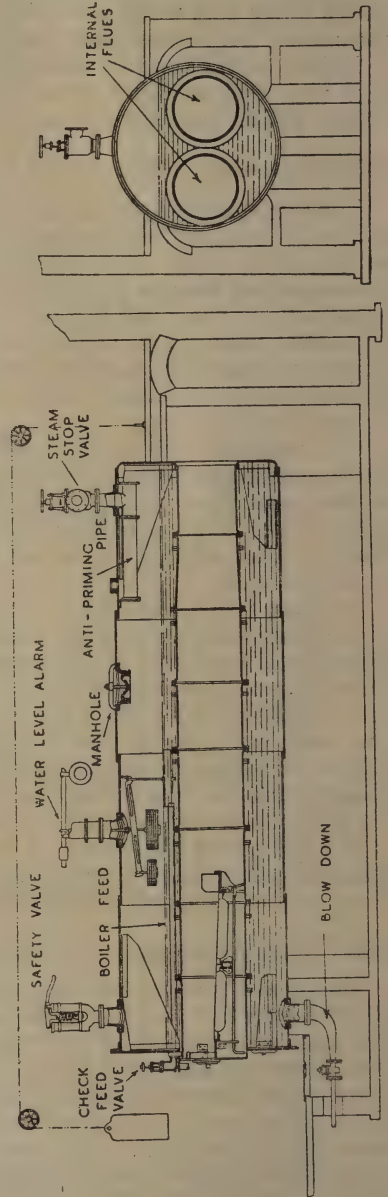


FIG. 7. Lancashire boiler.

repeating that a bright hot firebed must be maintained at all times if the best results are to be obtained. (See also "Radiation", Chapter 9.)

The use of mechanical stokers, mechanical draught and pre-heated air is therefore to be encouraged, although the application of these to an existing boiler should be considered in consultation with the makers of such equipment.

The heat absorption capacity of an internal flue has limits; if these are exceeded, structural defects may develop.

Apart from the nature of the surface provided, the design of the external flues does not lend itself to high efficiency. The flues are proportioned to give bodily access for cleaning, etc., as the primary object; as a result, it is probable that in many boilers layers of gas have only a brief contact—if any—with the external shell on their way to the main flue.

Moreover, the brickwork walls of the external flues must be heated every time steam is raised from cold or from a banked condition, and they continue to absorb heat during the steaming period, in proportion to the radiation losses of the setting as a whole.

Attention should be given to the brickwork sealing, as a defective setting can also cause considerable loss by allowing the gases to be short-circuited directly from the flue below the boiler into one of the side flues. A 30-ft.-long Lancashire boiler expands longitudinally about $\frac{3}{4}$ inch when heated, and the movement eventually causes spaces to form between the shell and back end and main seating brickwork. Through these spaces the gases flow into the side flues and thence direct into the chimney without giving up heat. Similarly, leakage spaces develop at the front end of the boiler and allow air to be drawn into the main flow of gas, with detrimental results. Cracks in the setting walls have the same effect, the importance of which has already been emphasised in Chapter II.

THE ECONOMIC BOILER

The Economic Boiler, illustrated in Fig. 8, consists of a cylindrical shell with two flat end plates. One or more flue tubes are disposed between the end plates below the centre of the boilers, the grate or other fuel-burning equipment being arranged at the front end of these flues.

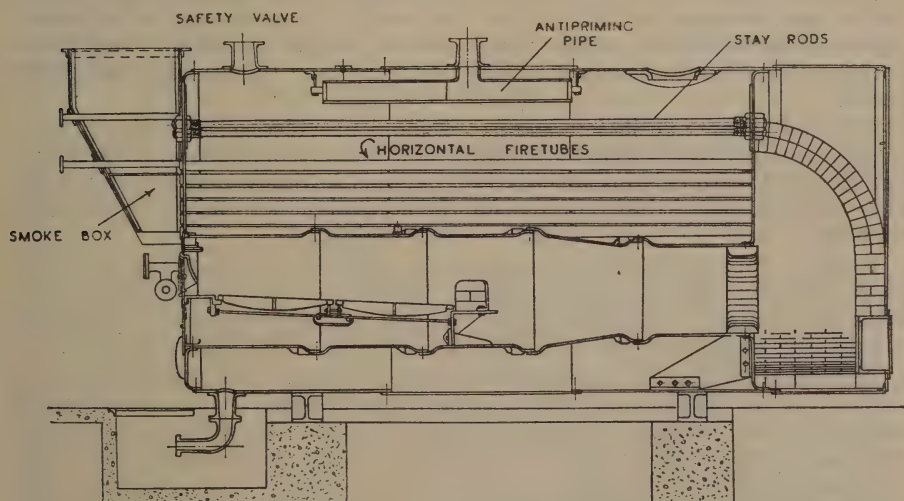


FIG. 8. Economic boiler.

The hot combustion gases traverse the flue tubes to the back of the boiler, where they enter a brick-lined combustion chamber in the case of a dry-back boiler or a water cooled combustion chamber in the case of a wet-back boiler. Here the gas path is reversed, and the gases travel to the front of the boiler

through a bank of smoke tubes located above the flues. These tubes are normally about 3 inches in diameter, and by their use the gas stream is broken up into a number of small elements materially increasing the rate and efficiency of heat transfer. The gases after passing through the smoke tubes are collected in a smoke-box, whence they are led to atmosphere.

Another type has a second bank of tubes superimposed, through which the gases traverse the boiler from front to back, being finally collected in a smoke-box at the back before being led to atmosphere.

For the same steam output an Economic boiler occupies about half the length of a Lancashire boiler complete with setting, and requires no expensive excavation, concrete raft, or brickwork setting. It is thus easy and cheap to install.

As a simple, straightforward boiler, without any ancillary aids to economy, it shows the highest thermal efficiency of all shell boilers. If supplied with a reasonable grade of fuel, efficiently operated and with adequate draught, it can show a thermal efficiency of up to 72 per cent. in the larger sizes (even higher figures than this have been obtained) all without the use of economisers, superheaters, or air-heaters, but these adjuncts can be easily incorporated if desired.

As an example of the high efficiency obtainable from an Economic boiler, we may take the case of one designed to give an evaporation of 10,000 lb. of steam per hour *f. and a.* 212° F. It would be 9 feet in diameter and 16 feet long over the tube plates or 21 feet long over the combustion chamber, whereas the equivalent Lancashire boiler would be 9 feet in diameter by 30 feet long, or 38 feet over the setting if without economiser. In addition a certain amount of space is required in front of the boiler for operating, and for tube cleaning, etc. For the Lancashire, the minimum for this purpose is about 9 feet, but if there is space 12 feet should be allowed.

The Economic boiler requires the same space for operating, but arrangements must be made to have a clear space equal to the length of the smoke tubes—though this need not be within the confines of the boiler room, as an opening of sufficient size can generally be arranged in the wall in front of the boiler.

Although Economic boilers are now seldom provided with brickwork settings, it is sometimes considered desirable, for the sake of appearance, to install one to match with existing installation, but this setting would in any case be only half the size of that required for the equivalent Lancashire boiler, thus showing a large saving in original cost and maintenance.

It will be appreciated that the smoke tubes materially increase the resistance to gas flow through the boiler, and the provision of an induced draught fan becomes necessary, but against this the chimney can be reduced in height and diameter as compared with that required for natural draught conditions.

As with other types of boilers, the quantity of steam that can be produced depends on the provision of sufficient grate area on which to burn the requisite amount of fuel, adequate draught to meet all conditions of burning, and the necessary amount and disposition of heating surface to absorb the heat generated on the grate. The larger sizes of Economic boilers are all fitted with mechanical stokers working in conjunction with induced-draught fans (and in some designs of grate with forced draught as well.)

Under these conditions a normal heat release of 425,000 B.t.u. per square foot of grate is obtainable with an average evaporation of 9 lbs. of steam, *f. and a.* 212° F., per lb. of coal.

The range of this type of boiler (with one bank of tubes) extends from 2,000 lb. of steam per hour (size 5 feet 6 inches diameter by 10 feet long) to

25,000 lb. of steam per hour (size 13 ft. 6 in. diameter by 17 feet long), these capacities being measured *f. and a.* 212° F. They are built for working pressures up to 225 lb./sq. in. in the largest sizes or 300 lb./sq. in. in the smaller ones.

The lengths given above will be increased by 3 to 5 feet by the addition of the combustion chamber. A single flue is incorporated for boilers up to 8 feet in diameter, and two flues in boilers above this size.

Approximately 10 to 16 per cent. of the total heating surface is provided by the flue tubes and as these tubes are subject to the radiant heat generated by the large mass of burning combustion products, the heat absorbing capacity of this surface is very high.

MODIFIED ECONOMIC BOILER TYPES

Within recent years, many manufacturers have modified their standard designs with a view to improving the heat transmission generally. Many of these modifications are not really new, being adaptations of arrangements previously used.

Some consist of tubular heating surface placed in the lower part of the shell, coupled with increased gas flow on the fire side, others have specially designed combustion chambers, some have improved forms of smoke tubes having a sinuous form. One maker has adopted the completely water-cooled chamber, characteristic of the Scotch Marine Boiler.

MARINE BOILERS

The fundamental requirements of a marine boiler are compactness, lightness, coupled with high endurance and ready accessibility, conflicting requirements that determine such basic differences as exist between marine boilers and land boilers. Some marine boilers, of course, find extensive use for miscellaneous purposes other than on ships.

Marine boilers are mainly of two types (*a*) the Scotch boiler and (*b*) water-tube marine boilers, of which there are many designs. The Scotch boiler, for many years standard equipment on ships, has a deserved reputation for reliability, for which reason it is still installed in many low-powered vessels, and as an auxiliary boiler on the larger vessels where its working pressure—restricted to a maximum of 250 lb./sq. in.—renders it unsuitable as a main power unit. It is a shell boiler similar in design to a wet back Economic boiler, but is much shorter and has a larger diameter that can generally accommodate three or four furnaces. Although basically designed for hand firing with coal, it is readily adapted for oil firing.

With developments in steam engineering techniques resulting in steam pressures, temperatures and unit evaporations outside the range of shell boilers, water-tube boilers have been specially designed to meet the requirements of marine service. In addition, the demand for light weight and small space requirements has called for special designs of water-tube boilers peculiarly suited to the sea service. Basically these fall into two types—the Header Type and the Small-tube Boiler, of which both two-drum and three-drum types are in general usage. For higher rated units a considerable amount of water cooling is incorporated in the furnace design in order to cut down refractories. Figs. 9 and 10 show in elevation and plan one type of 2-drum water-tube marine boiler.

Before the 1939-45 War considerable progress had taken place in firing marine water-tube boilers with mechanical stokers, but the almost complete replacement of coal by oil at sea has meant that all recent designs are arranged purely for oil burning, the combustion apparatus being of the pressure-jet type. The fundamental requirements of small space and light weight—coupled

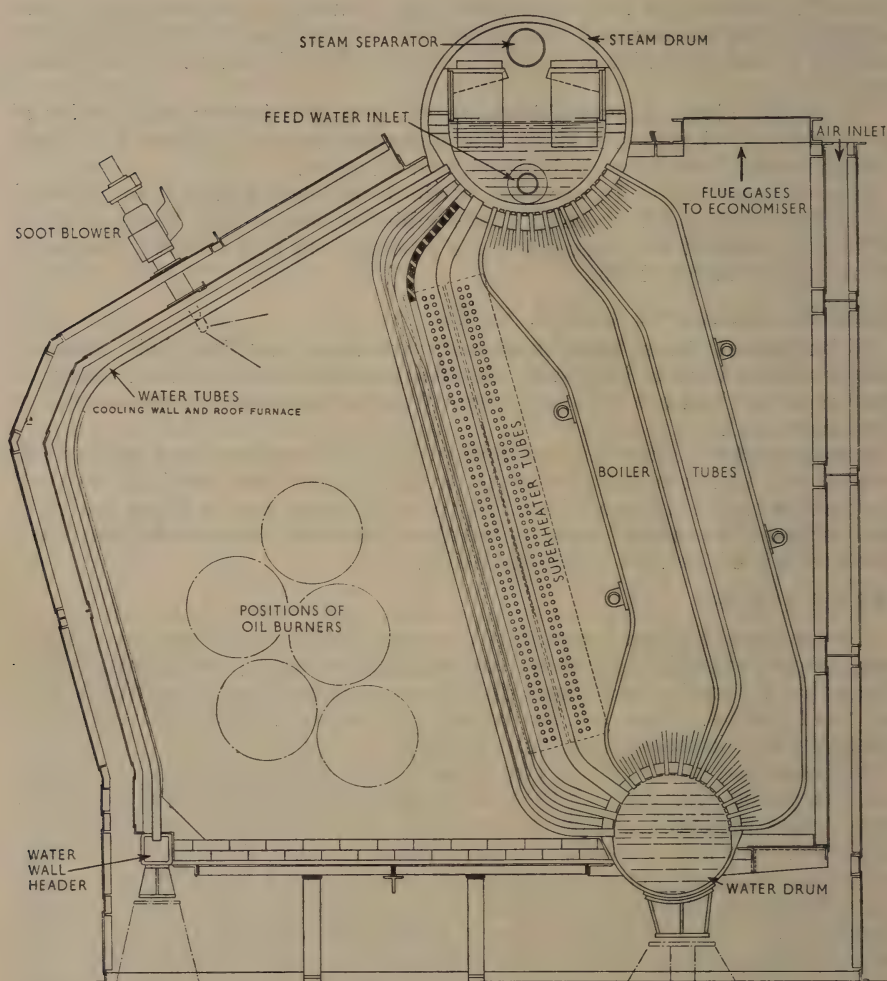


FIG. 9. Marine boiler ; 2-drum header type.
Elevation.

with high endurance and accessibility—have called for a very high standard of technical development. Secondary heating surface by air preheaters, economisers or a combination of both is standard practice; with steam temperatures above 750°F ., superheat control in some form or another is invariably incorporated for use during manoeuvring, and the practice of fitting automatic combustion control seems to be gaining favour.

WASTE HEAT BOILERS

In many manufacturing operations volumes of furnace gases at relatively high temperatures (up to $1,000^{\circ}\text{C}$.) are surplus to the main manufacturing process, but could be used to generate steam.

Where the quantity of gas is large, or the required steam pressure is high, installing a water-tube boiler plant is advantageous, but in other cases it is quite satisfactory to install waste heat boilers of the cylindrical horizontal smoke-tube type.

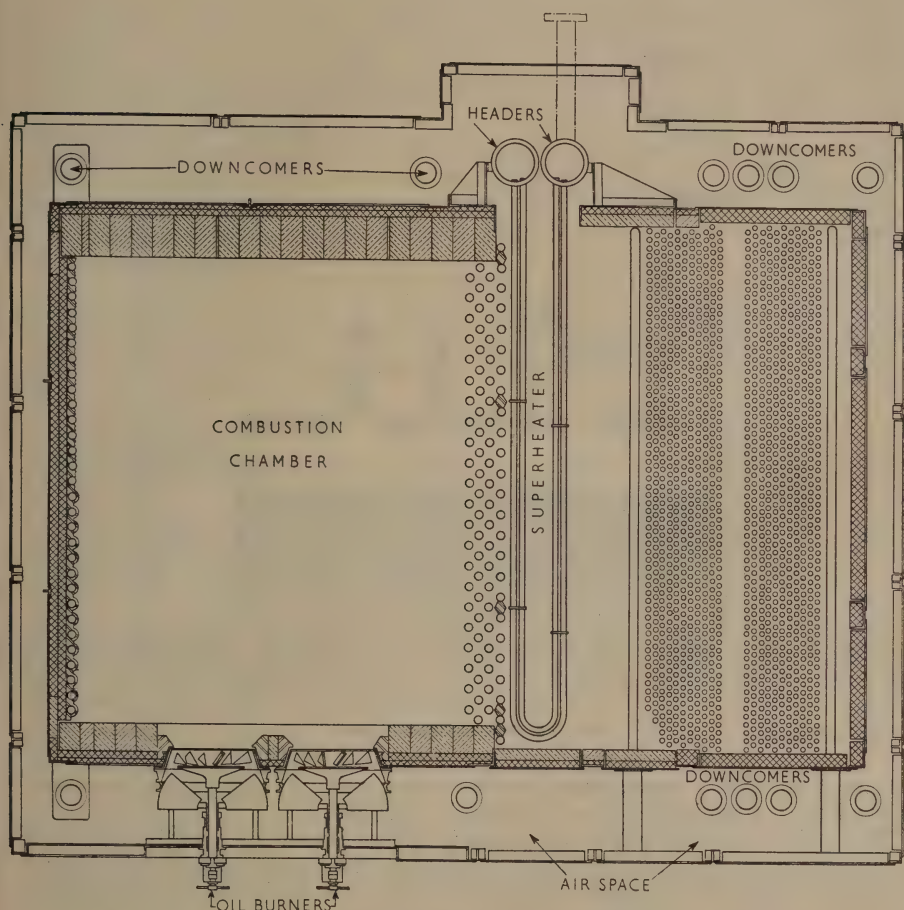


FIG. 10. Marine boiler ; 2-drum header type.
Plan.

The gases to be used are led in through ducts to a refractory-lined inlet chamber and then flow through smoke-tubes expanded into the front and back tube-plates and situated within the water space of the boiler. The cooled gases are collected in an outlet chamber before being drawn off to the chimney. A diagrammatic view of a waste heat boiler provided with an induced draught fan is shown in Fig. 11.

Since the temperatures and the hourly volumes of the gases available are capable of almost infinite variation over the field of industry, standardization of waste-heat boilers is not easy. Each boiler must, therefore, be designed with particular conditions in mind, but a few fundamental factors are common to all tubular waste-heat boilers.

As heat transmission is achieved mainly by convection, the insulating effect of gas films on the tube walls must be overcome by higher gas velocity. A fairly high gas pressure drop across the boiler is necessary to achieve this object, and an induced draught fan is thus an almost essential auxiliary. The sudden increase in velocity as the gas enters a tube mouth results in considerable additional turbulence extending for some distance into the tube, the

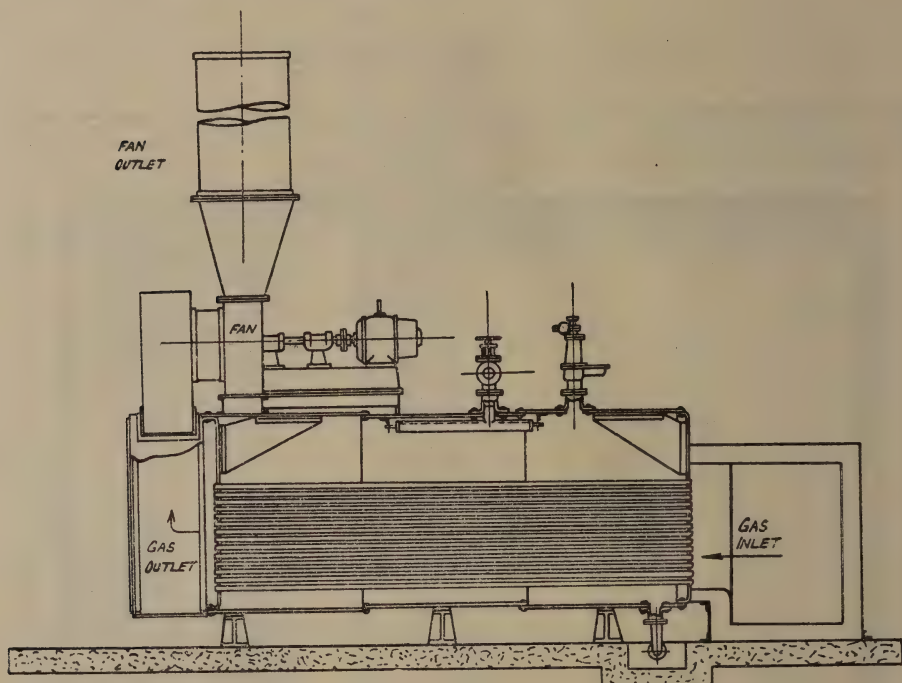


FIG. 11. Waste heat boiler.

extent of the effect depending upon the magnitude of gas pressure drop considered to be permissible in any given circumstances.

The ratio of tube length to diameter is also of importance as the gas must be allowed sufficient time to impart its heat to the water; ratios up to 150 : 1 have been applied. In modern boilers the ratio may be in the neighbourhood of 120 : 1, but when sinuous tubes are fitted it may be reduced to as low as 66 : 1, with consequent savings in boiler size and constructional cost.

Further, since evaporation takes place on the wetted surfaces of the tubes, space must be allowed for the free release of steam bubbles and the unretarded circulation of water. The tubes are in consequence fairly widely pitched, horizontally and vertically, and are provided with circulation lanes extending the full depth of the shell. Ample area is also required between the peripheries of the outer tubes and the shell.

In recent years boilers of the thimble-tube and force-circulation coil types have been used for waste heat utilisation, but as these applications are in the main in connection with internal-combustion engines, they are not discussed here. Waste heat boilers are discussed in detail in Chapter 21.

WATER-TUBE BOILERS

For pressures and capacities above those suitable for shell boilers previously described, the water-tube boiler must inevitably be selected. Boilers of this type are now being constructed for 5,000 lb./sq. in. g. pressure, and for capacities approaching four million lb./hr. per boiler. While its principal field of application is in the large installation and particularly the central power station plant, the water-tube boiler continues to find scope in the smaller

industrial unit, being readily adaptable to every kind of combustion process. By appropriate furnace design to suit the fuel available and in conjunction with suitable heat recovery plant its inherent flexibility in meeting load variations and its intrinsic high efficiency can be achieved in the smaller plant equally with the larger unit.

The choice between the shell boiler and the water-tube boiler in the smaller applications hinges upon economic considerations—first cost in relation to operation charges, type, quality and cost of fuel available, thermal efficiency and general characteristics of the steam demand, and in particular the nature of load fluctuations.

Water-tube boilers are characterised by the system of circulation employed, whether natural or forced. As these designations imply, the former type depends upon natural thermal-siphonic action to establish and maintain circulation while the latter incorporates a pumping unit in the water circuit to achieve the same object.

Natural circulation

The natural circulation type is applicable to operating pressures up to levels of the order of 2,700 lb./sq. in. beyond which the decreasing difference in density between water and steam imposes a limit. The forced circulation type can be adopted for any operating pressure, including pressures in the supercritical region, namely above 3,200 lb./sq. in.

In the natural circulation boiler water circulation is maintained by the difference in density between the relatively cooler water in the “downcomer” tubes and the steam-and-water mixture in the “riser” tubes in which steam generation is in progress by heat transfer from the hot gaseous products of combustion. The steam so generated is released from the riser tubes in one or more “steam and water” drums located at the highest point in the circuit, which in turn feed the downcomers.

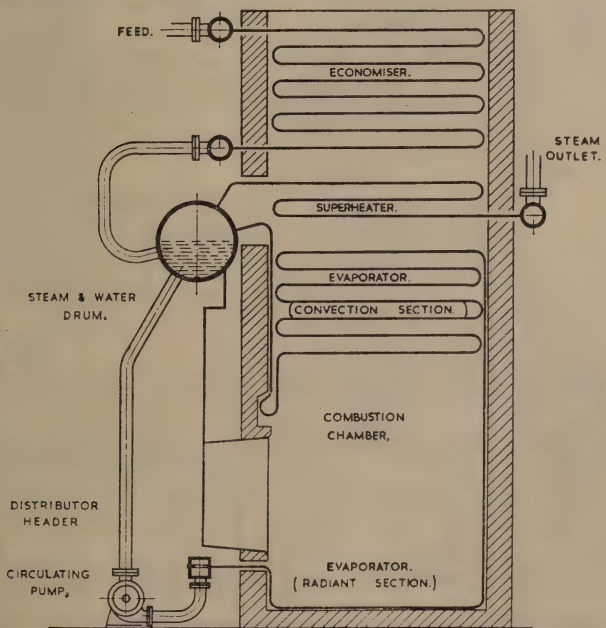


FIG. 12. Principle of forced circulation in water-tube boilers.

Since the rate of circulation is governed by the heat transfer rate, which is a function of boiler output, the disposition of riser and downcomer tubes must be carefully designed to ensure adequate circulation at all loads and to avoid reversal of flow in any section of the tube system with sudden change of load. With increasing pressures and consequent diminishing difference in relative densities of water and steam ample provision of unheated downcomer tubes becomes necessary and these are usually disposed entirely externally to the boiler heating surfaces.

As described later in this chapter, combustion chamber design for boilers of large output capacity has involved the development of the tall 'shaft' furnace, and the resulting elevated position of the main steam and water drum provides the increased hydraulic head required for the higher pressures associated with such capacities.

Forced circulation

Several types of forced circulation boilers have been developed, notably the 'once through' and the 'recirculation' types. The general principle of the latter is illustrated in Fig. 12. The former does not require a steam-and-water drum, the boiler feed pump forcing the water successively through heating, evaporating and superheating sections. Since there is no water storage capacity in the absence of a drum, close control of rate of feed of fuel, air and water is essential calling for automatic operation. A second complication is that the solids in

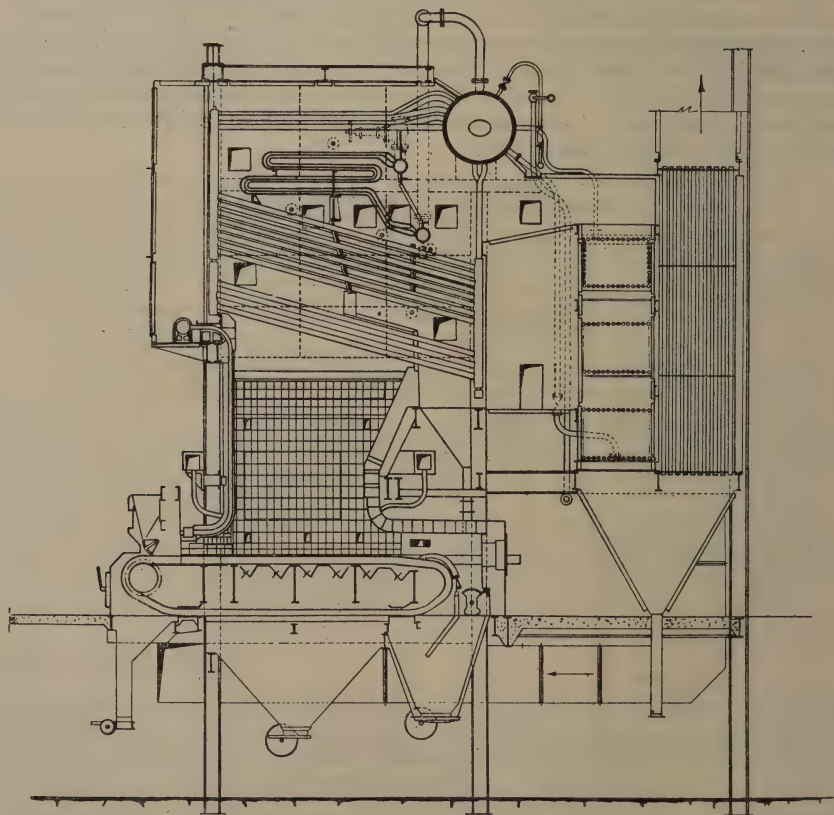


FIG. 13. Water-tube boiler ; sectional header type.

or suspension in the feed-water will be deposited at some point in the solution circuit with the risk of tube overheating, and provision must be made for cleaning or washing this section. In one design this limitation is overcome by incorporating an external separator into which the steam-and-water mixture from the generating section is discharged and whence the concentrated water can be blown down.

The recirculation type, often referred to as the "controlled circulation" type, has been more widely adopted than the former. This type incorporates a steam-and-water drum in which the water level is maintained by normal feed control methods, but circulation is maintained by one or more pumps in the water circuit drawing water from the drum and discharging into the generating tubes.

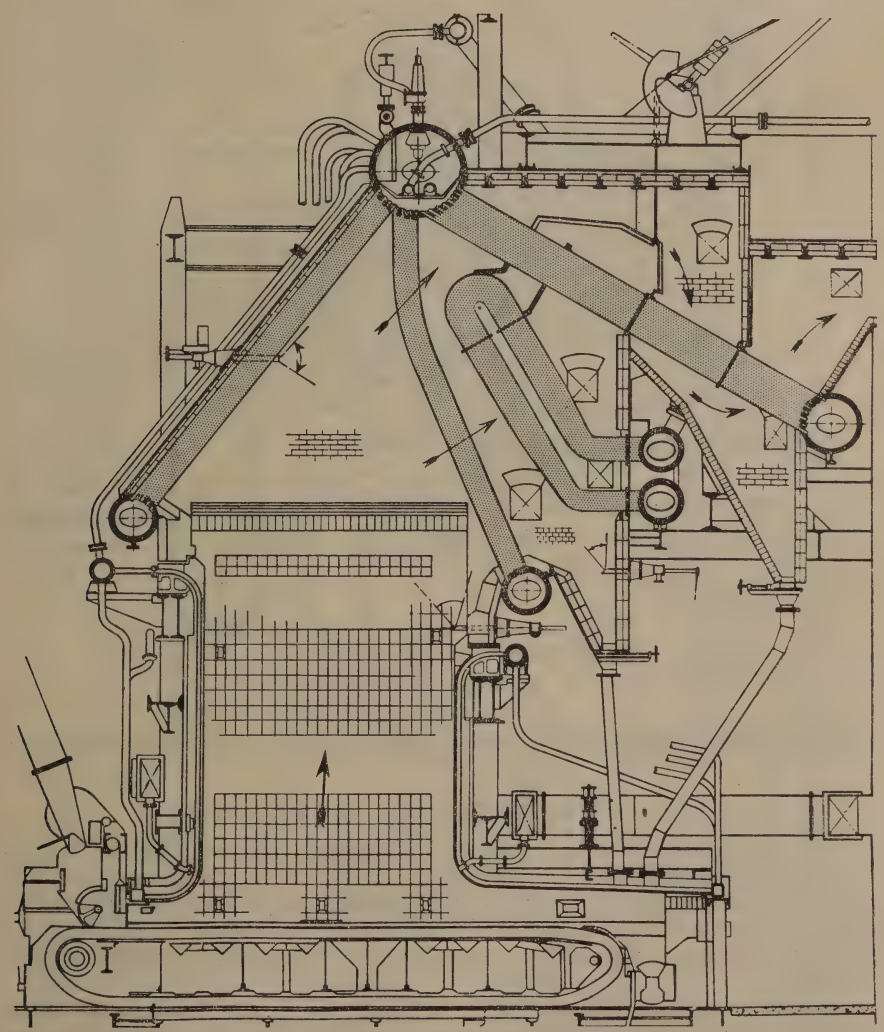


FIG. 14. Multi-drum water-tube boiler.

Shaded areas represent tube banks.

The feature of all forced circulation boilers is that small-bore tubes may be employed and these can be disposed about the combustion chamber and boiler in the most advantageous manner to suit the space available. This type of boiler is consequently specially suitable where space is restricted and a further advantage is the reduction in comparative over-all weight.

Natural circulation boilers may be further subdivided into *straight-tube* and *bent-tube* types in the smaller and medium capacity ranges more generally employed for industrial purposes. The former is exemplified in the *sectional header* type boiler shown in Fig. 13 and in the *multi-drum* type shown in Fig. 14. The *straight-tube* type possesses considerable advantages in facilitating internal inspection and tube replacement. The *bent-tube* boiler is usually

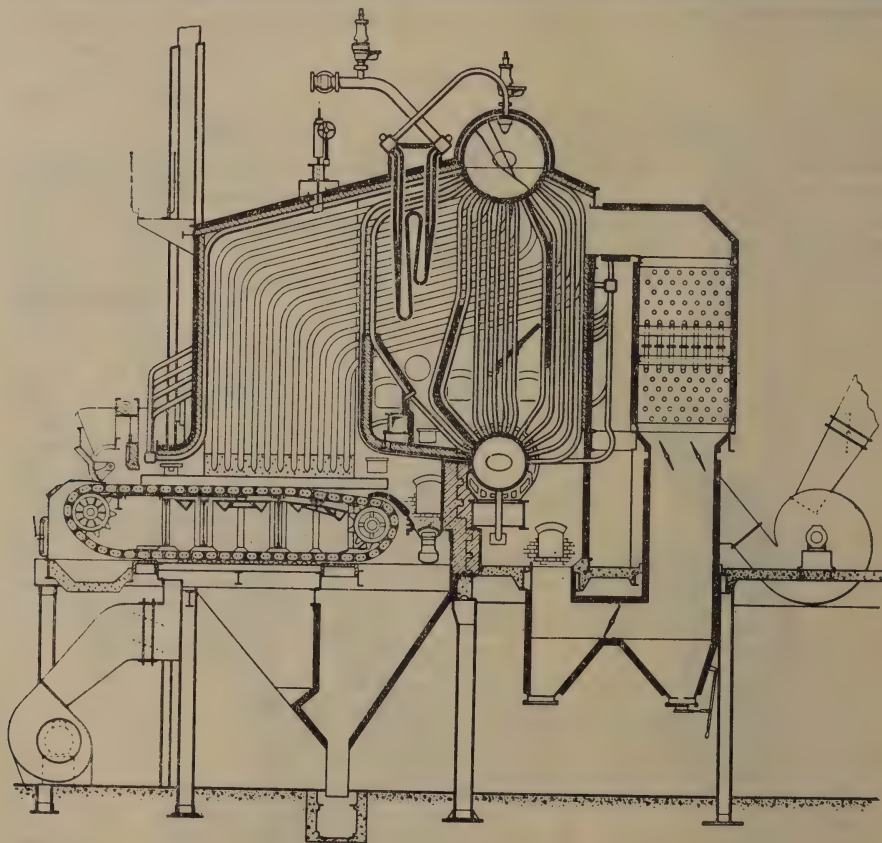


FIG. 15. Two-drum bent tube water-tube boiler.

of the multi-drum type, a characteristic design being shown in Fig. 15. The chief advantage of this type is the flexibility of the whole heating surface under the thermal stresses set up in operation. In general, the multi-drum boiler provides a larger reserve of water capacity than the sectional type; this consideration may influence its selection where rapid load fluctuations are expected.

A typical *controlled circulation boiler* is shown in Fig. 16. It will be noted that the furnace wall tube surface and the evaporator and economiser sections are each formed by continuous coils, welding being the method normally used to build up the respective lengths. Specially designed nozzle fittings in the dis-

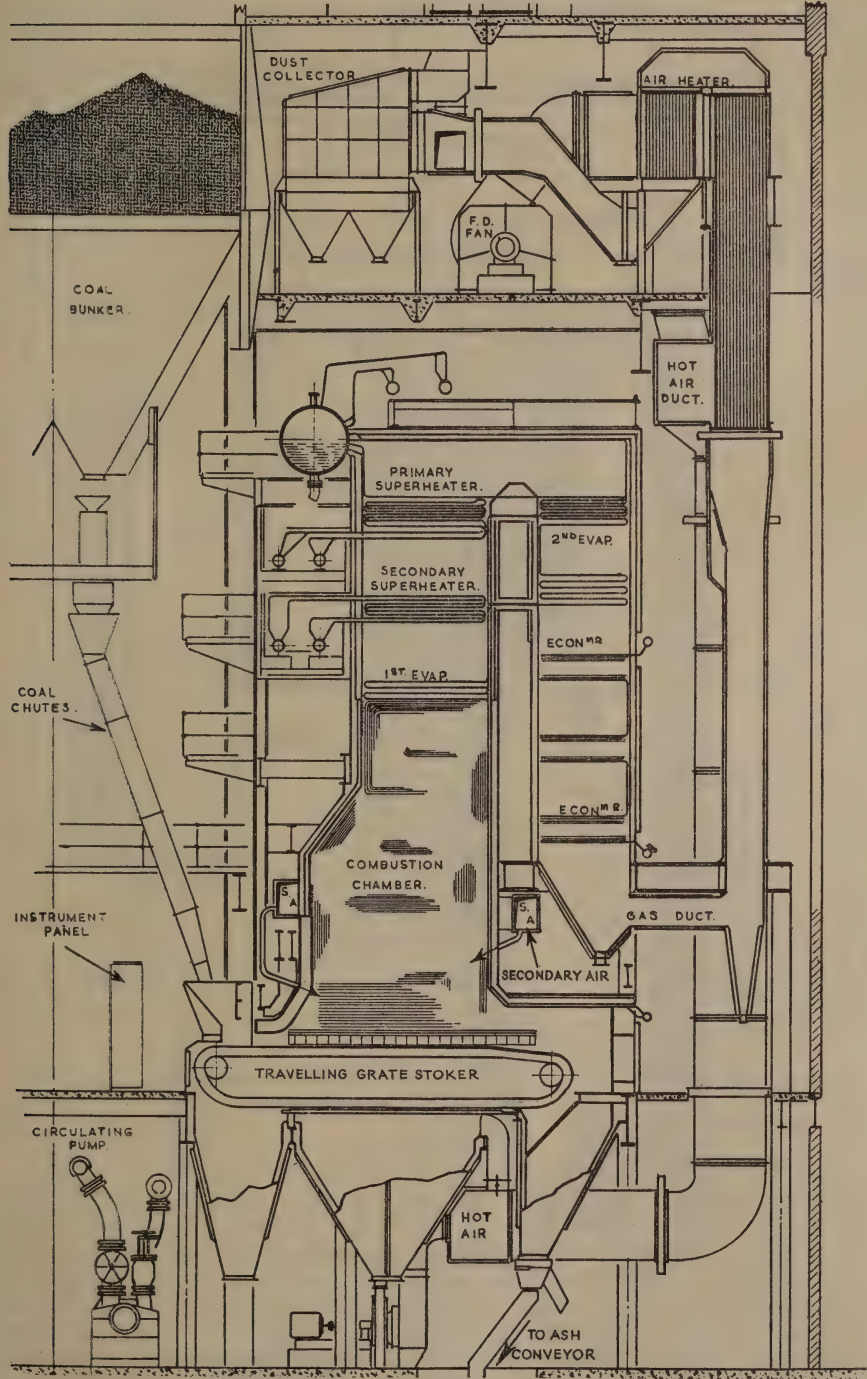


FIG. 16. Forced circulation water-tube boiler.

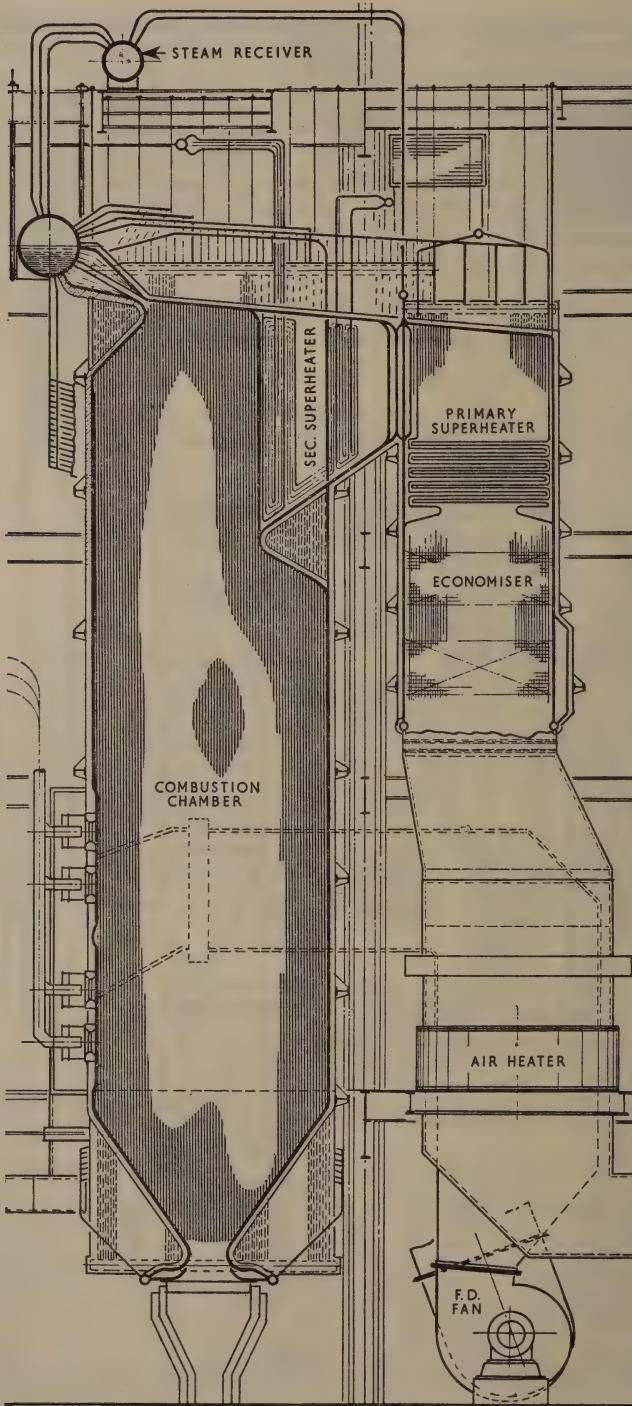


FIG. 17. High pressure, high capacity 60 MW unit water-tube boiler.

Evaporation, 550,000 lb. of steam per hour.
Steam pressure, 950 lb./sq. in.
Steam temperature, 925° F.

tributor headers ensure even distribution of water through each parallel circuit.

Examples of modern *high pressure large capacity* boilers are shown in Figs. 17 and 18. Characteristic features are referred to later.

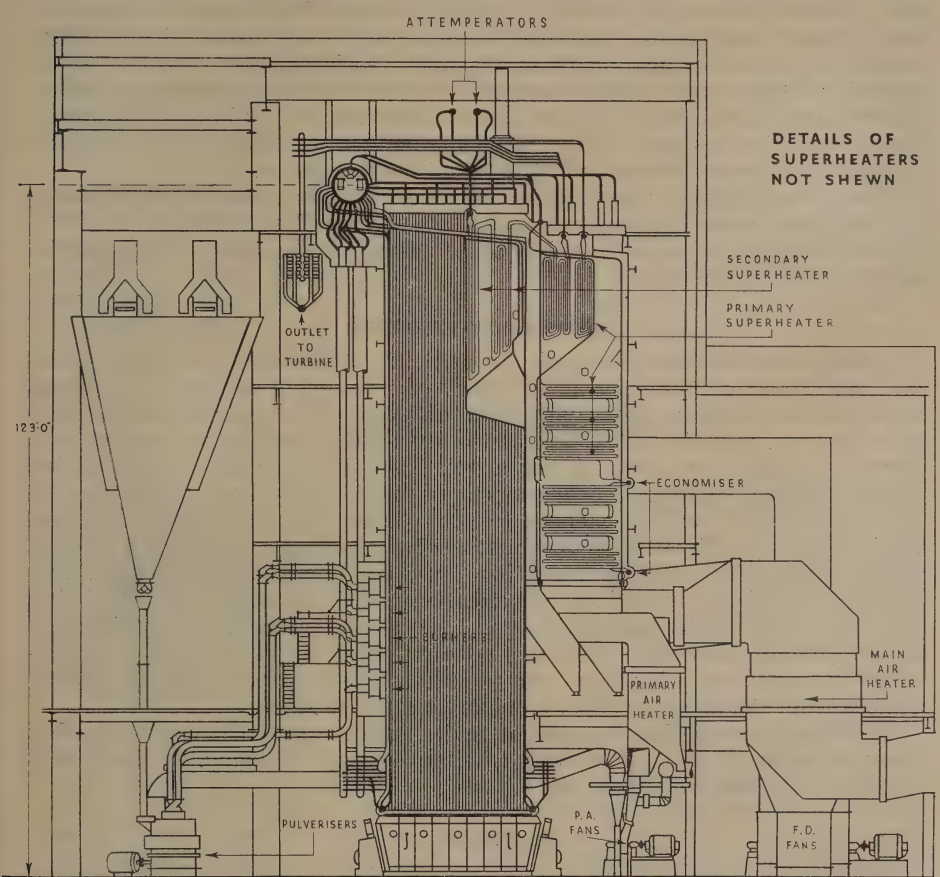


FIG. 18. High pressure, high capacity 100 MW unit water-tube boiler.
Evaporation 830,000 lb. steam per hour. Steam pressure 1,600 lb./sq. in.
Steam temperature 1,060°F. Twin furnace construction.

PACKAGED BOILERS

Modern water-tube boiler development has proceeded together with research work into the principles of combustion, heat transmission, metallurgy, water circulation, water treatment, and the fundamental physics underlying design. The experience gained in applying these principles to the large central station unit has been applied to the design of the relatively smaller industrial boiler plant. Some very compact steam generators known as *packaged boilers* have thus been made available for factory service operating within a range of evaporation from 300 to 40,000 lb./hr. and offering the flexibility in operation and high thermal efficiency characteristic of the water-tube design. Although they are available in the larger sizes, they are more commonly used to replace boilers within the range of shell boilers.

INFLUENCE OF STEAM POWER PLANT DEVELOPMENT ON BOILER DESIGN

The development of the water-tube boiler from the comparatively small type of unit in use at the beginning of the century to the modern high pressure, large capacity steam generator, has been governed by the general trend of steam power plant practice towards the use of high temperature, high pressure steam cycles with the high feed temperatures associated therewith. Increasing cost of fuel has given a strong impetus to the endeavour to secure the higher thermal efficiencies which these cycles give, and parallel development in metallurgical practice has provided both turbine builder and boiler maker with the materials necessary to meet constructional developments.

The theoretical gains from the use of high steam pressures and temperatures and high feed water temperatures are dealt with in Chapter 17.

Their influence upon water-tube boilers design will be appreciated from the following considerations.

EFFICIENCY CRITERIA

It will be evident from the typical heat balances of water-tube boilers given in Chapter 26 that the thermal efficiency of a complete installation depends upon two major factors: the complete combustion of the fuel with a minimum of excess air, and the extraction of the maximum possible amount of heat from the gaseous products of combustion. The heat lost in the combustion process, calculated from a measurement of unburned carbon in the ashes rejected, is to some extent a characteristic of the combustion appliance and method employed; by suitable combustion chamber design, taking into account such characteristics, the loss from this source may be reduced to a minimum. The boiler designer's main concern thereafter is the disposition of the boiler and superheater tube surface to secure the steam temperature specified, at design pressure, and the provision of adequate heat recovery surface in economiser or air-heater, or both, in order to extract the maximum possible amount of heat from the flue gases before exhausting to the stack.

Of recent years it has become of major importance to meet the further criterion of sustained availability at high operating efficiency. This aspect is given more detailed consideration below.

SUPERHEAT

A high steam temperature necessitates the highest practicable combustion chamber exit temperature to provide an adequate temperature gradient for efficient heat transfer through the superheater tubes. A limiting factor of vital importance to sustained satisfactory operation is, however, the influence of the softening and fusion temperatures of the ash-forming constituents of the coal (see Chap. 11). Unduly high furnace temperatures can only result in serious slagging difficulties in the superheater zone and the subsequent boiler tube passes when coal of low ash softening and fusion temperatures are used. The modern high capacity water-tube boiler normally embodies a completely water-tube-lined combustion space in which the maximum amount of heat is absorbed by radiation. A delicate problem in design is posed in aiming to achieve the required balance of temperatures, particularly where a low ash-fusion temperature coal is specified in conjunction with a high degree of superheat. In modern designs it is becoming common practice to provide only a screen of widely spaced boiler tubes constituting *radiant* rather than *convection* heating surface between furnace and superheater; in some designs for steam temperatures of the order of 1,050° F. no screen tubes are interposed before the superheater tube surface.

It is normal practice to provide some means of controlling the final steam temperature in order to provide for variations in fuel quality and other operational factors. This is achieved by one or more of several methods, such as the provision of means for partially by-passing the superheater tube surface by a suitable arrangement of dampers, by arranging the superheater in series with an attemperater in which partial de-superheating takes place under controlled conditions, by re-circulating inert gases or by admitting tertiary air into the superheater zone. In some designs applicable to pulverized-fuel-firing, superheat control can be achieved by tilting the burners, which in this application are disposed in the furnace corners, thus raising or lowering the zone of intense combustion within the combustion chamber. Other designs employing front-wall firing achieve the same object by disposing the burners uniformly through the height of the furnace chamber and providing means of varying the distribution of fuel to the various burner levels. Both methods provide a measure of control over the furnace temperature adjacent to the ash hopper outlet. Automatic control can be applied in all cases. In fact, it becomes essential if fine limits of temperature regulation are imposed by turbine room requirements.

FEED WATER TEMPERATURE

The high feed temperatures normally associated with the higher pressure cycles introduce problems in the provision of heat recovery surface. Two factors operate against the boiler designer; (a) the higher saturation temperature gives less scope for the absorption of heat in the boiler proper, (b) the higher feed temperature limits the amount of heat recovery possible in the economizer. To minimize the amount of heat lost in the flue gases discharged through the stack, greater air-heater surface must consequently be provided; this involves higher pre-heated air temperatures.

The situation has been met to some extent in the larger installations by the use of the steaming economiser. The economiser surface, in fact, becomes a forced circulation section of the boiler convection surface in that at certain loads steam may actually be generated in the final tube passes of the economiser. There still remains the need to increase air-heater surface and here a limitation is imposed by the method of combustion adopted. The travelling grate stoker operates satisfactorily with temperatures up to 350–400° F., depending upon the type of fuel, but above this limit damage is likely to be caused to grate links and mechanism.

Pulverized fuel firing, on the other hand, can with advantage utilize air at much higher temperatures, according to the extent of fuel drying required in the pulverizing mills (see Chapter 12). A rigid specification of high boiler plant efficiency when operating with a high pressure steam cycle may consequently involve recourse to pulverized fuel firing, apart from other considerations.

By the use of twin stokers the mechanical travelling grate stoker has been developed up to a total grate area of the order of 770 sq. ft., suitable to achieve a maximum boiler output—depending on the fuel quality—of 270,000 lb./hr. This factor accounts for the preponderance of pulverized fuel fired boilers in modern power station practice, where high pressure, high temperature cycles are now being adopted in unit burners of capacities up to, and even exceeding, 1,500,000 lb./hr., associated with 200 MW turbo-generators, and nine boilers of that approximate rating are (1957) under construction in Britain. Still higher ratings are in prospect.

FURNACE DESIGN

The earlier boilers were constructed with their heating surfaces arranged in close proximity to the grate surface. With the trend towards increased evaporative capacity to meet the development of larger turbo-generator sets, formation of smoke and other troubles were experienced in the attempt to increase combustion chamber and heat transfer ratings. The need consequently arose for a more scientific approach to furnace design, and a departure from earlier conceptions, which were based largely upon hand-firing practice.

It has been shown in Chapter 9 that the rate of radiant heat transmission in a combustion space is directly related to the fourth power of the Absolute flame temperature. The aim in design must accordingly be to establish as high a flame temperature as possible by restricting the amount of air supplied for combustion as closely as practicable to the theoretical minimum, while maintaining complete combustion of the fuel. The first development was to enlarge furnace dimensions, especially in the vertical direction, and to adopt refractory-lined walls to maintain the desired temperatures, providing air cooling to protect their refractory materials. Difficulties arose from slagging, the furnace temperature being often well above the fusion temperature of the coal ash. In consequence, molten ash deposited on the furnace walls either fluxed with the refractory material or "froze" upon its surface, causing rapid deterioration. Thus although the refractory lining might be able to withstand the designed furnace temperature, the heat input would be limited to a rate corresponding to the ash-fusion temperature of the fuel used, in order to avoid heavy brickwork maintenance costs.

It thus became necessary to limit furnace temperatures by incorporating a heat-absorbing surface in the furnace walls, and the modern water-tube boiler designed for the usual range of bituminous coals is characterized by its completely water-tube-lined combustion chamber. When using low volatile coals on a travelling grate stoker or as pulverized fuel, care must be taken to ensure that combustion is maintained by providing, adjacent to the ignition zone, local refractory lining to the furnace walls. One design using a block-covered tube type of wall construction found considerable scope in medium capacity boilers due to the ease with which the type of block selected, whether refractory-faced or bare metal, can be adapted to the particular combustion requirements. Another widely used design adopts a furnace wall construction formed by tubes having continuous welded longitudinal fins, refractory covering being applied where necessary. But, with increasing boiler capacities the bare tube wall construction with closely pitched tubes is being increasingly adopted.

DISPOSAL OF GRIT AND ASH

So far as disposal of ash is concerned, furnace design in Britain has, in the case of pulverized fuel firing, aimed at ensuring the discharge of ash in the "dry", i.e. unmolten, condition. 65-85 per cent. of the total ash in the fuel (in P.F. firing) passes through the boiler as fine grit suspended in the gases. The disposal of this material presents serious problems. In the interests of local amenity, and in accordance with the national policy of reducing air pollution (not only from smoke) the provision of special grit arresting and subsequent disposal equipment brings in its train serious economic problems, not only on account of the high capital cost of much grit and dust arresting equipment but also because of the cost of operating the plant and disposing of the dust and fly ash.

So far as ash is concerned two recent developments in furnace technique seem to offer contributions to the solution of these difficulties. One is the slag tap furnace; the other is the cyclone furnace. In the slag tap furnace the ash is deliberately kept in the molten condition by the provision of a primary

slagging furnace kept at a very high temperature, the molten ash being discharged either continuously or intermittently. This method of combustion is applicable to coals of not excessively high ash-fusion temperatures, and suitable, in practice, only to high load plant of the central power station type.

The cyclone furnace uses crushed—not necessarily pulverized—coal, and aims to reduce all the ash in the coal to the fluid state, thereby eliminating ash and carbon loss problems. The cyclone furnace is dealt with in greater detail in Chapter 12.

BOILER AVAILABILITY

Trends in the development of boiler plant have been towards greater unit capacities and the adoption of more advanced steam cycles. With the higher tube metal temperatures involved, coal quality has become of increasing significance, especially in regard to the amount and nature of the ash constituents.

Problems have thus arisen relating to the maintenance of efficient operation over long periods without the need for frequent shutting down for cleaning or repair—greater *boiler availability*. Sustained boiler availability is all the more important when, as with present practice, a single boiler of large capacity is associated with a single turbo-generator.

Such problems became of vital urgency in Britain in the early days of the 1939–45 War, and were already under close study by the Boiler Availability Committee set up in 1939 and representing the British (now Central) Electricity Authority, boiler manufacturers and research associations. The Committee's bulletins—which should be studied in this connection—have laid down operating procedures in regard to boiler maintenance and cleaning. These have gone far to alleviate the problem.

The research work done so far has suggested lines of development in boiler design; these may be summarized as follows:

- (1) General liberality of design avoiding excessive rates of combustion or of heat transmission.
- (2) Amply proportioned furnace volumes with correspondingly large area of heat-absorbing surfaces maintaining furnace exit temperature well below the ash fusion temperature of the fuel.
- (3) Adequate provision for admission of secondary air in such quantity, pressure and direction as to ensure thorough mixing of gaseous products of combustion.
- (4) Disposition of boiler tube surfaces in well-defined banks and in lateral spacing to establish regular temperature gradients throughout boiler, superheater and economiser and, by the adoption of wide pitching, to minimise the possibility of deposit formation.
- (5) Provision of access for on-load and off-load cleaning, by suitable tube spacing and arrangement at suitable points of pockets for dust or grit accumulations, with carefully located soot-blowers. In the larger boiler units the remote-controlled sequence-operated sootblowers are being increasingly regarded as necessary to ensure adequate on-load cleaning.

To these features of design may be added the contribution made to the overall availability of plant by recent developments in welding technique enabling the adoption of all-welded pipe-work connections and employed to particular advantage in superheater and economiser construction.

The modern water-tube boiler of whatever capacity has, however, become a piece of apparatus requiring accurate instrumentation and skilful control. These aspects are dealt with in fuller detail in other chapters of this book.

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See also REFERENCES appended to Chaps. 11 and 15.

CHAPTER 15

BOILER AUXILIARY PLANT

CHAPTER 14 deals with the main components of steam boilers. Although the items discussed in this chapter are termed Auxiliary Plant the parts they play are just as essential in the integrated whole of a boiler plant. Some are essential for the proper operation of the boiler, others for complying with the requirements of the law. Many are incorporated in the basic design of the plant.

BOILER MOUNTINGS**SAFETY VALVES**

Under the Boiler Regulations of Britain, and of most other countries, every boiler must have at least two safety valves, each capable of discharging the total peak evaporation of the boiler. The valves may be arranged on a single chest. The compulsory requirement to have two valves on each boiler is made on the assumption that if one valve fails to act for any reason the other will function. This is not, of course, by itself a sufficient safeguard, and the safety valves should receive frequent attention.

There are three main types of safety valves: (a) dead weight, (b) lever or steelyard, and (c) spring-loaded. Each type is made in a variety of patterns, the more modern having means for locking and adjustment, so arranged that no unauthorised person shall tamper with the setting of the valves. The safety valves should be tested periodically to ensure their reliable operation, and in accordance with boiler insurance requirements.

The discharge from a safety valve should always be so arranged that indication is given to the operator when it is blowing off steam because when this occurs there can be a prodigious waste of fuel. It is sometimes found that one safety valve in a range of boilers has been set to blow off at a slightly lower pressure than the others so that it "feathers" at working pressure—i.e. blows off steam gently, but continuously. This is bad practice as not only is a lot of steam wasted but the seat of the valve becomes scored and in due course the valve feathers at any pressure.

HIGH AND LOW WATER ALARMS

The British Boiler Regulations also require that a steam boiler be equipped with either a fusible plug (if of shell type) or a High and Low Water Alarm which makes a sound that can be easily recognized by the operator.

There are two main types of alarms: (a) internal, and (b) external. Internal alarms usually consist of two floats, one at each end of a long arm suspended from the crown of the boiler shell. The arm is attached in such a manner as to pivot about an axis so that one float acts at a dangerously high level, the other at a dangerously low level. At correct working levels of the water in the boiler the low water float lies on the surface of the water, the high water float being suspended clear of the surface, and the system is in equilibrium. When the water level falls, the low level float drops and actuates a lever which operates a steam whistle. When the water level rises to the level of the top float, the upward movement of the bottom float being restricted, this becomes buoyant and causes the arm to tilt in the same direction as before so that the whistle again sounds. The principle can be incorporated in a lever-type safety valve.

The internal type of alarm is now superseded by the external types, of which there are two main categories: (i) the float type and (ii) the thermostatic type. These consist of chambers mounted at the normal working level of the water in the boiler and are connected to the steam and water spaces. The floats respond to change in level of the water in the boiler and, at predetermined high and low positions, actuate a steam whistle, or two whistles of different notes, one for high water conditions and the other for low. The thermostatic type consists of rods that expand and contract according to whether they are in steam or in water. In conditions of normal working level the upper rod is immersed in steam and the lower one in water. If through a rise in the water level the upper rod becomes immersed in water it contracts and if the lower rod becomes immersed in steam it expands. Either movement actuates an electric circuit switch which usually causes a bell to ring.

WATER GAUGES

All boilers of evaporative capacity exceeding 300 lb. of steam per hour must be fitted with two water gauges. For boilers pressures up to 250 lb./sq. in. it is usual to fit tubular gauges which must be protected; the protection usually consists of a shield of specially toughened glass. Higher pressure boilers are usually fitted with the flat plate type of gauge.

Water gauges should be so placed that the water level can be easily seen by the operator and so arranged that the lowest visible section of the glass is higher than the minimum working level. It is good practice to test water gauges and cocks once per shift by opening and closing the cocks in the prescribed manner.

BOILER FEED VALVE

The feed check valve is situated on the boiler shell or steam drum, usually just below the low water level. It is essentially a non-return valve to prevent water from escaping from the boiler should the pressure in the feed line, for any reason, be less than that of the boiler. A stop valve must be inserted between the non-return valve and the boiler. This may be incorporated in the feed check valve but the arrangement should be such that when the stop valve is closed it will be possible to remove the non-return valve for inspection and for adjustment and minor repairs while the boiler continues in operation. When more than one boiler is being fed by a single pump the stop valve can be manipulated to control the rate of feed to the boilers.

Internal feed pipes are provided and care should be taken that the possibly relatively cold feed water does not impinge on anything—such as the tube plate of an economic boiler, or a riveted joint—that would be affected adversely by the resultant local stress variations.

BLOW-DOWN VALVE

The blow-down valve has usually three important functions to perform: (1) de-concentration of the boiler water and prevent the solids content rising above the prescribed limits (see Chapter 16); (2) ejection of sludge and solids precipitated from the boiler water and settling at the bottom of the boiler; (3) emptying of the boiler for inspection or other purpose.

The blow-downs may be continuously or intermittently operated. The former method is most effective in de-concentrating the boiler to prevent priming or foaming. In many cases it is located near the surface of the water in the boiler shell, or top steam drum.

The intermittent blow-down valve is used for the systematic ejection of unwanted solid matter deposited from the boiler water, as well as for emptying

the boiler when necessary. It is, of course, an essential fitting and must be of first-class structure. It is necessarily placed at the lowest part of the boiler; consequently it is frequently in a position where it is not continuously under the eye of the operator. The discharge from the valve should, if possible, be piped to a place where it can be easily inspected, as undetected leakage can cause serious waste of fuel.

When two or more boilers discharge their blow-down into the same pipe the valves should be operable by only one key that is locked in position when the valve is open and removable only when it is closed. In this way only one blow-down valve in a bank of boilers can be opened at one time.

BOILER FEED PUMPS AND INJECTORS

Except in the very rare circumstances when there is sufficient gravitational head available, energy must be expended to supply water to a boiler. The selection of the feed system depends on the following, among many, factors:

- (a) *Reliability.* It is essential that the equipment can be relied on, with complete confidence, to function properly under any conditions that may be imposed upon it.
- (b) *Availability.* This may be considered along with Reliability and covers the amount of maintenance that will be needed. It may be desirable that the boiler plant can operate if necessary as an independent unit. The availability could be reduced if the system is dependent on a supply of electricity or power from another source.
- (c) *Supervision.* In some plants the operator has duties additional to looking after the boiler. It is necessary that the feed system selected should be suitable for such circumstances.
- (d) *Initial cost.* A feed system that is unsuitable or inefficient can be so costly, due to effects on production or even on running costs, that after a short period the initial cost may be small in comparison. The conventional systems such as are discussed here have long established a reputation for the reliability that is associated with simplicity and good design at reasonable cost.

METHODS OF PROVIDING FEED WATER

There are in general three main methods of feeding water into a boiler : by injector, by displacement pump and by centrifugal pump.

Injectors. In this system water is fed by means of a steam jet and a suitable

arrangement of nozzles which convert some of the kinetic energy of the steam into pressure energy. Injectors have a lower initial cost than pumps, occupy less space and incur practically no maintenance cost. They have a high thermal efficiency since all the heat in the steam used either provides energy to raise the pressure of the feed water or is recovered in the feed water. If they are operated carelessly, however, much heated water can be lost by way of the overflow. As they are usually unable to feed water with an initial temperature above 90° F., injectors are not suitable for any system where a high percentage of condensate is recovered, and their installation may tend to deter condensate recovery. Fig. 1 illustrates the principle of the steam injector.

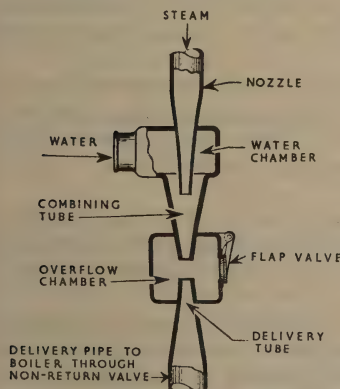


FIG. 1. Diagram illustrating the principle of the steam injector.

The range of injectors available can deal with from 300 lb. to over 100,000 lb. of cold water per hour. Owing, however, to the limitations already referred to, and as it is necessary to use about 1 lb. steam to inject 10 lb. of water, injectors are more suited for small plants where the load is fairly constant and not heavy, and where there is little condensate available for return. They are sometimes installed as a stand-by unit to reciprocating feed pumps.

Displacement Pumps. In reciprocating pumps the feed water is displaced from the suction to the discharge by the reciprocating motion of a bucket or plunger. When the steam piston and the water bucket are on a common shaft the reciprocating pump is known as a *direct-acting feed pump*. Pumps of this type are traditional in Britain—especially in shell boiler plants—where they have established a reputation for reliability. The higher speed pumps initially require, as a rule, less steam, but as they are more liable to the effects of wear they may eventually take more. The steam consumption of a direct acting feed pump may vary between 2 per cent. and 5 per cent. of the boiler output. The simplex pump, which has a single barrel (one water bucket) is the commonest; it is a slow speed pump usually working at 30–50 feet per minute. On pumps on boilers evaporating up to 1,200 lb. of steam per hour, this may represent over 40 double strokes per minute at the slowest speed. The piston valve gear, slide valve and water end valves thus wear more rapidly on very small pumps than on larger pumps operating at 10–14 double strokes per minute when fully loaded.

Small pumps have usually fixed cut-offs and take steam for practically the whole of the stroke, with a small allowance for cushioning effect on the piston at the end of the stroke. Larger pumps have variable cut-offs but take steam for at least 0.7 of the stroke. Thus while the mechanical efficiency of a direct-acting feed pump may be high the thermal efficiency is low.

Only about 2 per cent. of the heat from the fuel used to raise the steam needed by the feed pump is represented by the pumping work done; up to 70 per cent. of the heat from the fuel is contained in the exhaust from a direct-acting feed pump, consequently it is essential that as much as possible of the heat in the exhaust steam be recovered. This steam, being usually contaminated with oil, is generally utilized to heat the boiler feed water either in a feed water heater or by passing it through a coil in the feed tank.

A disadvantage of the simplex feed pump is the pulsating flow of the discharge, which may be harmful to the fittings between the pump and the boiler. The pulsations can be reduced by fitting an air bottle on the discharge of the pump but the greatest improvement can be made by using multi-barrel pumps.

The duplex pump, which has two water barrels, is the commonest multi-barrel pump. Its main characteristic is that the slide valve on one cylinder is controlled by a lever connected to the piston rod of the other cylinder. Thus it can be arranged that the discharges overlap, more uniform flow of water being thus obtained.

Duplex pumps generally work at higher speeds, up to 80 ft. per minute; though they may initially take less steam they are more subject to wear and are usually found to be taking more steam than a corresponding simplex pump would take.

Direct-acting feed pumps are manufactured in a range of sizes to discharge up to about 200,000 lb./hr. and are most suitable for boiler pressures up to 200 lb./sq. in. For higher pressures it is usual to install a centrifugal pump or a reciprocating pump motor-driven through reduction gearing. Multi-throw arrangements of the latter type have a fairly steady discharge; generally they require less power than centrifugal pumps of similar capacity. The discharge

pressure of multi-throw pumps increases with the load, but the differential between full load and no load is not so great as that of centrifugal pumps, where the pressure falls as the load increases.

Centrifugal Pumps. In these pumps the feed water flows by reason of the centrifugal force imparted to the water by the rotation of one or more impellers through which the liquid flows from the suction to the discharge. Except in Britain, the centrifugal pump is used almost universally for boiler feed purposes. In Britain it is generally found in boiler plants evaporating over 50,000 lb./hr. at pressures greater than 250 lb./sq. in. and in very small boiler plants up to 2,000 lb./hr. They are now even being installed in boiler plants between these limits, a field of application that has long been exclusive to reciprocating pumps.

The mechanical efficiency of a centrifugal pump depends very much on its size, large pumps, e.g. those handling up to 75,000 gal./hr. have an optimum efficiency of about 83 per cent., while pumps designed for 5,000 gal./hr. have an optimum efficiency nearer 65 per cent. In general the smaller the pump the lower is the efficiency. Typical centrifugal pump characteristics are shown in Fig. 2. It will be noticed that pressure falls with output. A badly designed

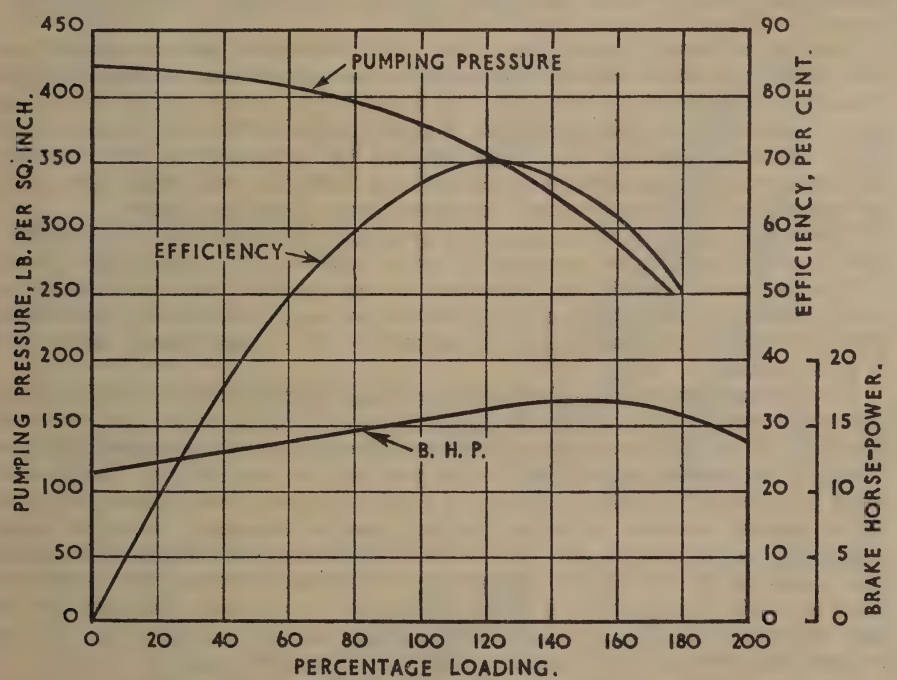


FIG. 2. Centrifugal pump characteristics.

pump may have a pressure characteristic as shown in Fig. 3. A pump working under such conditions is liable to oscillate between two rates of delivery, A and B, and each change from one point to the other causes a pressure impulse or (as it is commonly known) a "water hammer" to be set up in the pipe line.

The falling characteristic is particularly important when two or more centrifugal pumps are operating in parallel. If the pumps do not have similar characteristics there is the possibility that one pump will give its maximum discharge while the others are practically idling and heating up. The slope of a pressure characteristic curve should not be unduly steep, otherwise there

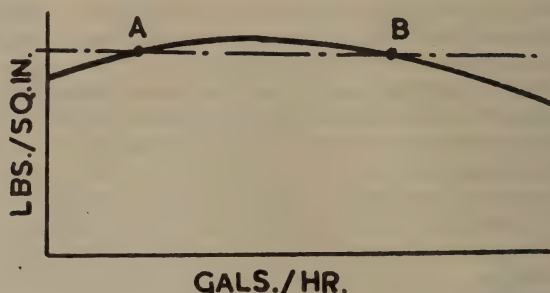


FIG. 3. Undesirable pressure/load characteristics for a centrifugal feed pump.

will be a large pressure difference between full-load and no-load conditions. The permissible pressure increase may vary from about 8 per cent. with a constant-speed electrical drive to perhaps 10 per cent., or slightly more, when a steam turbine drive is used. Too large a pressure increase affects the design of pressure-bearing appliances, such as economisers, feed heaters, etc., located between the pump and the boiler.

Centrifugal Pump Construction. As a result of impeller action, the pressure and velocity of water leaving the impeller are higher than on entering. The velocity is converted to still higher pressure in the pump casing before the water is discharged. This conversion is accomplished either in a volute casing, or by diffuser vanes set in a ring around the periphery of the impeller. Diffusers are recommended, because volutes cause unequal radial thrusts to be exerted on the impeller shaft, imposing heavy bending stresses.

When the total pressure cannot be produced efficiently by one impeller, two or more impellers are arranged in series, resulting in a multi-stage pump.

Pressure varies directly as the square of the speed; thus a turbine-driven pump which runs at speeds up to 6,000 r.p.m. may require only two stages while electrically-driven pumps will, because of their lower speeds, have eight or more stages.

A feed pump impeller is completely surrounded with water at its discharge pressure except, of course, for the impeller eye where the water is at the inlet pressure. There is thus set up an axial thrust equal to the pressure difference through the impeller multiplied by the area of the impeller eye. This thrust must be balanced, usually by means of a balance piston on the shaft. One face of this piston is connected to the discharge end of the pump, the other being connected to the suction end. The force thus exerted on the piston balances the axial thrust set up by the pressure differences across the impellers. Another method of balancing this axial thrust is to arrange the impellers so that the respective thrusts tend to cancel out, but this method usually also requires the provision of a thrust bearing to absorb any residual forces.

Selection of Drive for Centrifugal Pump. Small pumps are usually electrically driven but for boiler steam pressures of the order of 250 lb./sq. in. and upwards the choice can be made between turbine and electric drives. In industrial plants if conditions are suitable, it is usual to install turbine-driven feed pumps, as they are generally more reliable and the exhaust steam can be utilized for heating the feed water, either by discharging it through a nozzle into the feed tank or—as is most common—in the de-aerator. In larger plants, or at power stations where electricity is generated in very efficient sets, it is usually thought economic to install an electrically-driven pump. The overall efficiency of the main turbine, alternator and electrically driven pump being considered to be higher than that of a turbine-driven pump.

PUMPING HOT FEED WATER

The saving by using hot condensate as boiler feed water is two-fold, firstly because its use results in a direct economy in fuel, and secondly because its purity will do much to prevent scale in the boiler feed system. It is found, however, that valuable condensate is often wasted because of the difficulties of pumping hot water; consequently tons of fuel represented in the hot condensate are run down the drain while more fuel is used in heating cold feed water. While it is agreed that there are theoretical as well as practical limits to handling hot condensate, a very substantial economy can be effected if the necessary consideration is given to the design of the pump, suction piping and position of feed tank. Experience has shown that the source of the trouble is usually the suction piping or the position of the feed tank.

The secret of successfully pumping hot feed water is attention to the correct conditions on the suction side of the pump. Flow from a pump is caused by the pump, but the flow of a liquid into a pump is caused by forces outside the pump. A pump should, therefore, be so arranged that, from the source of feed water supply the pressure created in the suction chamber of the pump is greater than that at which the water will vaporize. When water is being pumped from a tank containing a free surface, the difference between

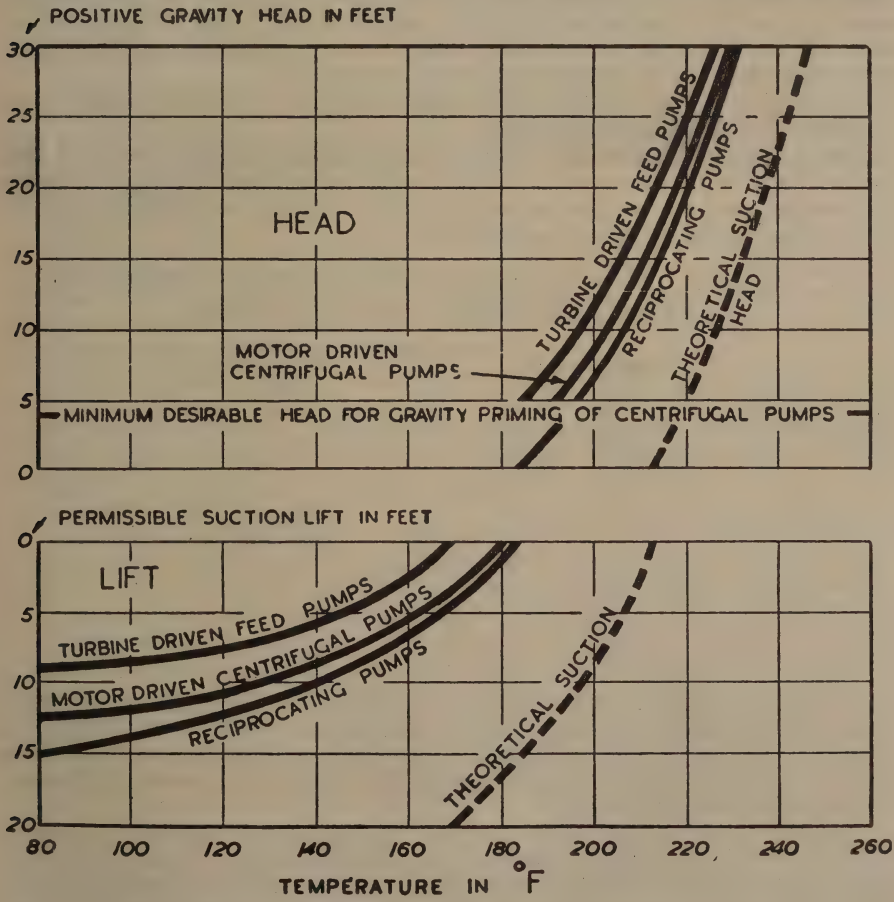


FIG. 4. Suction heads permissible for standard designs of pumps.

the pressure on the surface of the water and the pressure in the suction chamber of the pump is the only pressure available to cause the flow of liquid into the pump. Fig. 4 shows the usual pressure difference allowed (expressed in feet of water) for the average installation of various types of pump of standard design. The discontinuous line shows the theoretical suction head, i.e. pressure, corresponding to the temperature at which the water is at the point of boiling. The pressure difference allowed includes a reasonable allowance for the friction losses in the suction pipe line and in suction passages and valves in the pump, as well as a margin to cause the liquid to follow the motion of the moving parts of the pump without vaporization occurring. Suction heads must generally be greater for high speed or large capacities than for low speed or small capacities.

Before water can flow into a pump, the air or vapour in the suction line must be evacuated sufficiently to reduce the pressure in the pump in order to cause the liquid to flow into the suction chamber. Displacement pumps do this automatically when they are started. In centrifugal pumps, the liquid must be present in the first impeller before the centrifugal force to cause flow can be imparted to the liquid; this requirement necessitates that the pump be so placed relatively to the source of water supply that the water flows by gravity into the impeller. If this cannot be arranged, special priming devices must be used to cause the evacuation of the air and flood the pump with water and establish the flow from the feed tank into the pump. A centrifugal boiler feed pump should never be arranged to have a suction lift.

The information given in graphical form in Fig. 4 is given in tabular form in Table 1 for direct acting pumps.

The suction piping from the feed tank to the pump should be as short and as free from bends as possible. Sharp right-angled bends should certainly be avoided, and the suction piping and valves should be designed so as to reduce the friction losses to a minimum.

TABLE 1. SUCTION LIFT AND HEAD FOR VARIOUS FEED TEMPERATURES DIRECT-ACTING FEED PUMPS

<i>Temperature °F.</i>				<i>Lift to suction valves: feet</i>
130	..	..	..	10
150	..	..	..	7
170	..	..	..	2
175	..	..	..	0
				<i>Head over suction valves: feet</i>
190	..	..	..	5
200	..	..	..	10
210	..	..	..	15
212	..	..	..	17

It will be seen, from the figures given in Table 1 that with the temperature above 175° F. the feed tank must be placed higher than the feed pump to ensure a pressure at the pump suction. The head required between the pump suction and the water level in the tank must be sufficient to prevent the water vaporizing in the pump end.

For feed temperatures above 212° F. it is necessary to provide a suction head of 17 feet *plus* a head equal to the gauge pressure corresponding to the feed temperature. If the feed temperature is above 212° F. and the heating is all done in the feed tank, the tank must be sealed and it should be placed

at least 17 feet above the feed pump, or a booster pump must be provided to give the necessary suction head. Alternatively the feed water can be heated in a direct contact or a surface heater, suitable booster pumps being provided to give the necessary pressure at the suction of the feed pump.

FEED WATER HEATERS

Heat should not be allowed to escape from any thermal circuit if it can be recovered or utilized, because otherwise this heat must be replaced at the expense of additional fuel. In steam cycles waste heat is often utilized to pre-heat the boiler feed water.

The total amount of heat in one gallon of condensate recovered at 180° F. exceeds that in a gallon of feed water at 60° F. by 1,200 B.t.u. Thus, if the boiler efficiency is 65 per cent. the heat recovered represents a saving of 1,850 B.t.u., equal to about 1/7 lb. of a fuel of calorific value 13,000 B.t.u./lb. Apart from effecting useful economy in fuel this method of heat recovery has the additional advantage that the condensed water is free from the scale-forming compounds present in the raw water, thus assisting in keeping down boiler cleaning charges.

Feed water may also be heated by the direct injection of hot water or of exhaust steam. If either of these is contaminated, indirect recovery in a heat exchanger will be necessary; this may consist of a single coil in the feed water tank or a surface heater.

Surface heaters (of which a wide range is manufactured) belong to two categories—low pressure heaters, which heat the feed water up to a maximum of 215° F. and are placed before the feed pump, and high pressure heaters, in which the feed water is heated to above 215° F., the latter being situated on the discharge side of the feed pump.

Where a steam engine is used to generate power, the feed water can be heated by discharging sufficient of the exhaust steam into the feed tank. In a multi-expansion engine steam may be tapped off between the expansion stages. In either arrangement provision should be made to ensure that a vacuum cannot be created in the steam pipe and thereby cause feed water to be drawn into the engine cylinder.

In larger plants exhaust steam from the turbine-driven feed pump, or low pressure steam bled from the main turbine may be used to de-aerate the boiler feed water. Gas cannot remain in solution when water is heated to boiling point. Thus by boiling the feed water by means of exhaust steam the dissolved oxygen is expelled, a point of equal importance to the fuel saving effected by pre-heating the feed water.

Steam that has been bled from the main turbine after it has done some useful work can be used to pre-heat the boiler feed water to within 100–120 deg. F. of the temperature of the saturated steam in the boiler. This, known as *Regenerative Heating*, greatly increases the combined overall thermal efficiency of turbo-alternator and boiler. To obtain the theoretical maximum efficiency would require an infinite number of heaters in series, but in practice the number is seldom more than five or six. This is because each additional heater gives less gain in efficiency than the one preceding it, and while the first heater might save 5·6 per cent. of fuel, a fifth heater would give only 0·5 per cent. additional saving. A common arrangement is to have one low pressure heater and a de-aerator before the feed pump and three or four high pressure heaters after the pump.

High pressure heaters, which are of the enclosed type, consist of a cylindrical shell housing a tubular element. The shell is designed to suit the pressure of the heating steam, which flows over the external surface of the tubes through

which the feed water is pumped at the boiler feed pressure. To allow for the different relative expansions of the tubes and the shell, various types of "floating" headers, U-tubes, etc., have been evolved.

Pumping Losses. The velocity of the water through the heater tubes is an important factor in minimizing pumping losses. Moderate velocities are desirable and they usually vary from about four feet per second to six feet per second. The size and cost of the heater can be reduced by increasing the water velocity and, consequently, the heat transfer coefficient. The external diameters of the tube vary from $\frac{1}{2}$ in. to $1\frac{1}{2}$ in. and the number required to give the necessary cross-sectional area is directly related to the water velocity adopted.

The tubular surface area depends upon the weight of water to be heated, its temperature rise, the heat transfer coefficient, and the mean temperature difference between the steam and the water. The required tube length is a function of the surface area and the number and diameter of the tubes as determined by the water velocity. The total length may be divided into a number of *passes* which will vary according to the permissible height or length of the heater, but when the two tube-plate construction is used, the length between the tube-plates should not be more than about 100 tube diameters, otherwise tube supporting plates may be necessary. It will be appreciated that these interfere with free internal flow of steam.

When feed water heating by steam bled from the turbine is carried to the practical upper limit at the higher pressure ranges it may be necessary to provide a steaming economiser or a greater amount of air heating surface; the latter may, in turn, render it advisable to use firing methods and systems that can use air at high temperatures. (See Chap. 8.)

BOILER FANS

Fans may be provided for supplying air or removing the products of combustion from a boiler furnace. Much of the improved performance claimed for the modern internally-fired multi-tubular boiler can be attributed to the use of higher gas velocities, which of course must be paid for in fan power. A saving in the height, and consequently the cost, of a chimney may result but it must be remembered that most authorities stipulate a minimum chimney height.

The use of fan draught allows the maximum amount of heat to be abstracted from the products of combustion before they are discharged into the chimney; it makes possible enhanced rates of combustion of low-grade fuels together with higher furnace temperatures and higher rates of heat transfer; and it permits rapid control of the boiler over a wide range of output. Fan draught may be applied as forced, induced or balanced draught, according to the particular requirements of the boiler and fuels used.

Boiler fans are necessarily of the centrifugal type. Centrifugal fans are classified according to their blade inclination and the three basic types are (a) forward curved blade fans, (b) radial blade fans, and (c) backward curved blade fans. There are, of course, several intermediate types of fan blades but each basic type has its own distinctive characteristics.

The type of blading affects the volumetric capacity, pressure generated, power required, efficiency and operating speed. In theory any type of fan can be designed to suit the requirements of volume and pressure and their maximum efficiency will not vary greatly. However, the backward curved blade type is mostly used for forced draught. It is a high speed fan, which is useful for causing pressure variations due to speed control, and unlike the other basic types its power consumption or brake horse-power reaches a maximum

which cannot be exceeded. This eliminates the necessity for overload protection as it should be impossible to overload the driving motor even if the resistance of the system be suddenly reduced.

Desirable as these features may be, backward curved blade type fans are not generally used for creating induced draught. This is mainly because curved blades tend to trap grit and soot ; they become heavily coated, causing the fan to get out of balance and accelerate wear and tear. Radial blades on fans tend to be self-cleaning and this type is used mainly on induced draught fans. It is a characteristic of radial blade fans that they are larger in diameter than the other types and require a slower driver. The size of the induced draught fan is further increased relative to the forced draught fan since it has to handle approximately twice the volume of gases due to the higher temperatures. Often in order to reduce the size of induced draught fans they are fitted with blades which are forward-curved but have radial tips to promote self-cleaning.

Fans with straight blades which are backward-inclined and of aerofoil section are now being installed for induced draught duties. The blade form and arrangement are such that dust build-up does not occur and in normal induced draught conditions erosive action is minimised. The horse-power absorbed by these fans, like that of the backward curved blade fan, is self-limiting and it is claimed that they are very efficient over a wide range of operation.

Having decided on the type of fan, it must be designed for volume and pressure. From the characteristic curves shown in Fig. 5 and Fig. 6 it will be

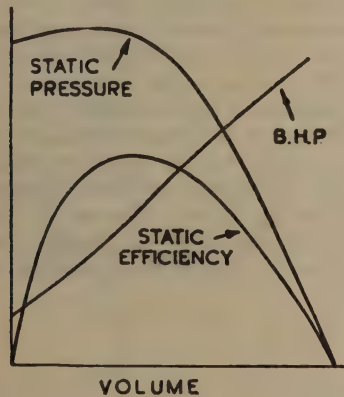


FIG. 5. Characteristic curves of fan with backward curved blades.

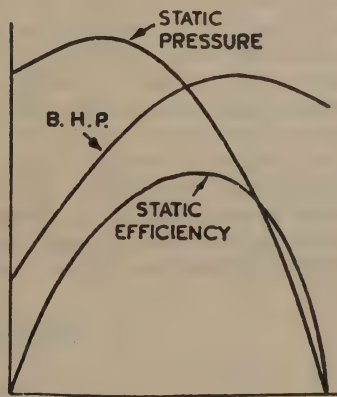


FIG. 6. Characteristic curves of fan with radial blades.

seen that each fan can be designed for a maximum efficiency at a particular load. In boiler work a fan is usually designed for full load conditions with a margin of about 20 per cent. overload, although the requirements of the boiler plant and the nature of firing must be taken into account. The boiler load must be related to the volume of air required for combustion or the volume of the flue gases. Thus the temperature of the air or flue gases and the CO_2 content of the flue gases must be known. A fan that has been designed for products of combustion containing 12 per cent. of CO_2 will be overloaded if the CO_2 content is only 8 per cent. In this case the fan pressure will fall; this may tend to increase the CO_2 content of the flue gases but it will be noticed that the response of the boiler to changes of load will be very sluggish. In order to keep the fan size to a minimum it should deal with gases at the

lowest possible temperature. Forced draught fans, for example, should be installed before any airheater and not after.

The resistance of the system is overcome by the static pressure developed by the fan. The total pressure produced by a fan is the sum of the static and velocity heads and these can be measured in a flue or ducting by means of manometers, as is shown in Fig. 7.

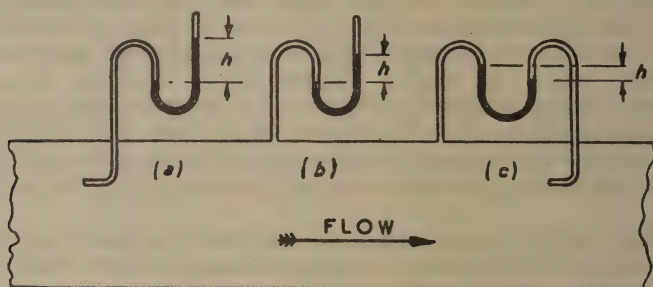


FIG. 7. Manometers used to measure static and velocity heads.

The manometer at (a) is measuring the total pressure produced; the static head is indicated by a manometer of the type shown at (b) but to obtain the velocity head it is necessary to insert a tube into and facing the main stream of air and to connect its other end to the wall of the ducting as at (c) in the figure. (See Chapter 10.)

Fan Control. To operate a fan with maximum economy, some form of control must be introduced to relate the pressure and volume of the discharge to the boiler load. There is a wide choice of controls but these must be examined in relation to the fan driver. If the fan is coupled directly to a constant speed motor, the output may be regulated by a damper on the discharge side or by vanes or louvers on the fan inlet. By partially closing an outlet damper while maintaining the original fan speed, the pressure on the discharge side is dissipated in overcoming the artificially produced damper resistance, and there is little reduction of load on the driver. The use of inlet-vane or louver control modifies the basic characteristics of pressure and volume as is illustrated by curve C in Fig. 8; curve A being the original charac-

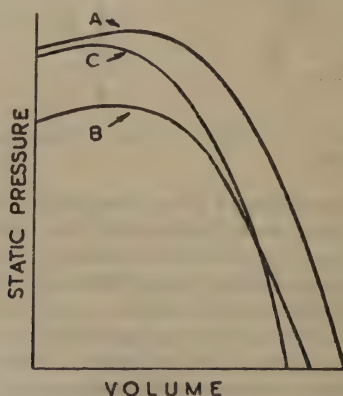


FIG. 8. Fan characteristics with different methods of control.

teristic. The reduction in both pressure and volume results in a greater reduction in power than with outlet damper control. Inlet-louver control is used

primarily for induced draught fans where inlet-vanes are not suitable due to the grit and dust. Inlet-vanes are most often found on forced draught fans.

The pressure and volume can be controlled by varying the fan speed which can be effected by a variable speed driver, or by the use of a hydraulic coupling or variable gears between the driver and the fan. Variable speed drivers are most economical to run and here the range choice is extensive and includes d.c. electric motors, steam turbines or a.c. slip ring motors, though the latter must be augmented by damper control as the variation in speed is effected in steps unless expensive controllers are used. The basic characteristic as the result of varying the fan speed is illustrated by the curve B in Fig. 8.

Selection of the control method will result from evaluation of such factors as fuel being burned, initial cost and type of firing equipment, operating cost, initial cost, operating cost, range of capacity, regulation available, speed of response to demand change, simplicity of operation, reliability, life and maintenance. Fig. 9 shows typical power requirements of an induced draught fan incorporating various methods of control.

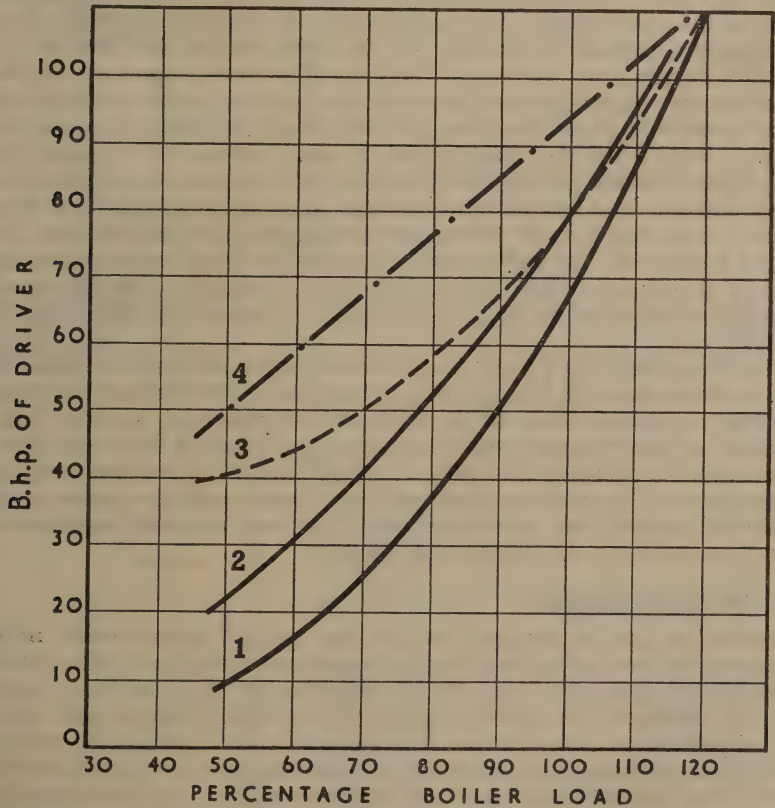


FIG. 9. Effect of method of control on power requirements of an induced draught fan:

- 1. Variable speed d.c. motor.
- 2. Hydraulic coupling adjustable speed.
- 3. Inlet Louvre Control (constant fan speed).
- 4. Damper Control (constant fan speed).

SUPERHEATERS

The necessity of superheated steam for economic power generation has been discussed in Chapter 17. Superheaters are also installed to boost the thermal

efficiency of a boiler plant. This occurs when more heat is available in the flue gases than can be absorbed by the boiler feed water without danger of steaming in the economiser. The installation of a superheater is equivalent to increasing the boiler heating surface, and lowers the flue gas temperature to the economiser. If superheated steam is not suitable for the specific process a de-superheater should be installed. (See Chapter 17.)

Most superheaters are installed within the boiler setting and receive heat from the flue gases from the boiler furnace. These *integral superheaters* are generally of the convection type, absorbing heat from the gases of combustion which sweep over them. In some instances externally or separately fired superheaters have to be provided, but in general steam-raising practice these are uncommon and for the present purpose can be disregarded.

HEAT TRANSMISSION IN A SUPERHEATER

For effective heat transmission in a superheater the mean temperature difference between the gas and steam sides of the elements must be greater than 250°F . In the convection type of superheater the resistances to heat flow are (a) the gas film external to the tube, (b) the metal wall of the tube and (c) the steam film on the inner surface of the tube. The most important of these is the gas film and the final steam temperature is related to the gas temperature and the mass velocity of the gases (i.e. the weight of gases in lb. per second per square foot of free gas passage area). A small increase in the mass velocity has a proportionately greater effect on heat transmission than a small rise in gas temperature. Also, as cross-flow heat exchangers have a higher heat transfer coefficient than longitudinal flow heat exchangers, superheaters that can be arranged so that the hot flue gases flow across the tubes require less surface area than those where the gases tend to flow along the tubes. The gas flow must also be arranged to avoid local rises of temperature which can cause tube failure.

On the steam side, the primary requirement is that all the superheater tubes should receive a uniform flow of steam. The steam velocity should be arranged to assume a critical value at the intended normal load, so that the best conditions for heat transmission are set up as this tends to lower the tube wall temperature. To promote this velocity there must be a pressure drop across the superheater. The pressure drop varies, of course, with the degree of superheat that is required and may vary from 2 per cent. on small superheaters to nearer 7 per cent. on the largest installations.

TYPES OF SUPERHEATER

Superheaters can be designed to suit any type of steam boiler, although on certain shell boilers the final steam temperature may have to be restricted by the limited space available for the superheater. In a vertical cross-tube boiler, for instance, the space available is extremely limited and the only practical position is in the uptake. The diameter of the uptake so restricts the size of the superheater that, in effect, it forms an extension of the steam pipe placed in the path of the products of combustion. In a vertical boiler having vertical smoke-tubes a greater area of superheater surface is possible because the superheater can be arranged over the top tube-plate in the form of a continuous coil.

Provision for still greater area can be made when a boiler of the type shown in Fig. 10 is under consideration, and in this example the superheater may be made up of a number of "hairpin" bends located in the combustion chamber space. This design allows for much higher superheat temperatures than those mentioned above.

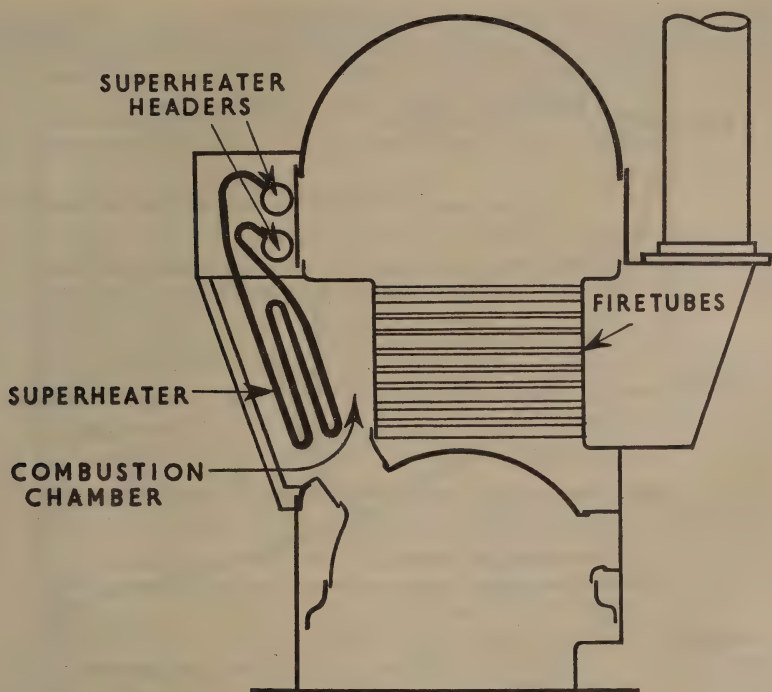


FIG. 10. Superheater applied to a vertical boiler.

In a Lancashire boiler the superheater is situated at the rear end in the downtake at the exit of the furnace tubes, as shown in Fig. 11. In this type of boiler the temperature on the fire side of the boiler falls progressively from

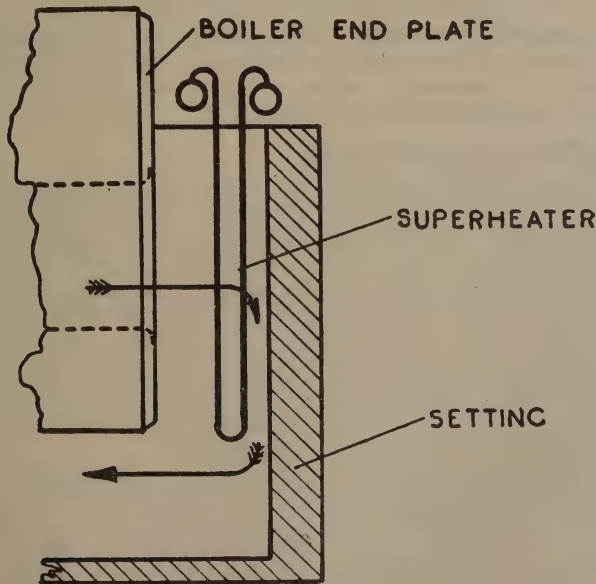


FIG. 11. Superheater arranged for a Lancashire boiler.

the furnace to the main chimney flue opening. An approximate temperature curve for a 30 feet long Lancashire boiler is shown in Fig. 12 and it will be

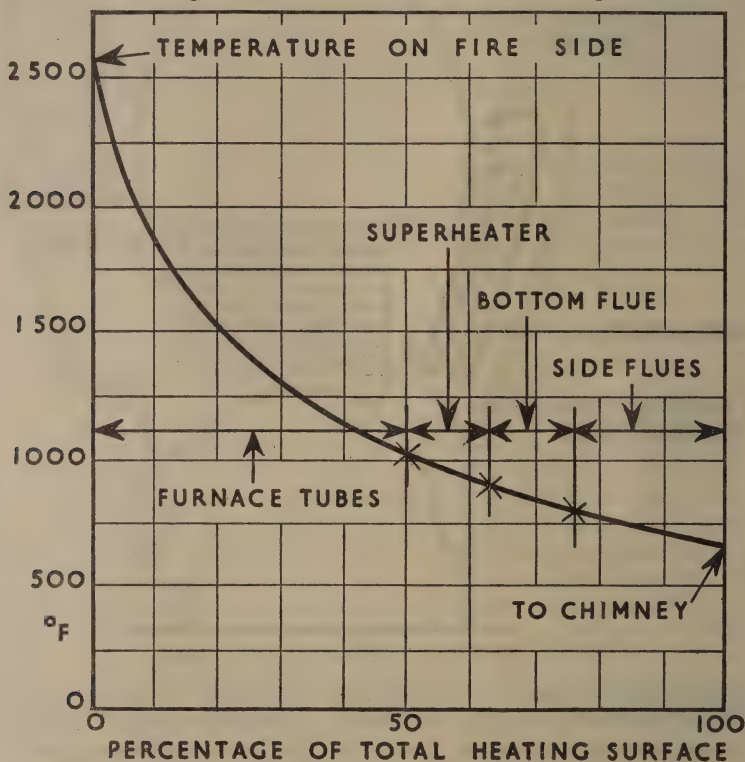


FIG. 12. Temperature curve for a Lancashire boiler.

seen that the greatest temperature drop occurs in the furnace tubes. The flue gas temperature at the exit of the furnace tubes may be of the order of $1,000^{\circ}\text{F}$. Thus, the maximum degree of superheat that can normally be obtained in a Lancashire boiler is about 250°F .

ECONOMIC BOILER SUPERHEATERS

As in the case of the Lancashire boiler, the furnace temperature of an economic boiler may be about $2,600^{\circ}\text{F}$. However, due to the shorter length of an economic boiler, the gas temperature will be lowered only to about $1,600^{\circ}\text{F}$. at the exit of the furnace tubes, a further drop to $1,300^{\circ}\text{F}$. occurring in the combustion chamber. The temperature will then gradually fall, as the gases pass along the smoke tubes, to possibly about 550°F . at the uptake end of the tubes. When only a few degrees of superheat are required, as for instance where steam has to be transmitted over a distance for process purposes, a superheater may be installed in the smoke box. For higher superheat temperatures the superheater is usually installed at the back-end at the exit of the furnace tubes, as in the Lancashire boiler.

Where the bore of the smoke tubes permits, the superheater can be constructed in the form of a series of U-tubes inserted into the tubes from the smokebox, the saturated and superheated steam heaters being arranged in the smokebox space. For even higher temperatures the U-tubes are replaced by a number of single tubes connecting with a series of superheater elements arranged in the upper part of the combustion chamber.

The U-tube form of superheater can be applied also to the stationery locomotive boiler, but in this application some of the upper rows of smoke tubes are replaced by tubes of larger bore capable of receiving the elements, the header or headers being placed in the smokebox. When only a moderate rise in steam temperature is desired, this space can be utilized to house superheater surface consisting of continuous tubing of suitable size.

WATER-TUBE BOILER SUPERHEATERS

Water-tube boilers are usually designed to generate superheated steam and the boiler heating surface can be arranged to accommodate the desired superheater. Specified temperatures of steam leaving the superheater influence selection of the type of boiler selected.

The design of superheater depends on many factors but a practical upper limit of steam temperature is set by the materials available for superheater construction. Steam temperatures as high as 1,050° F. have been maintained in service, but in normal industrial installations the steam temperature is restricted to below 850° F. to allow of the maximum use of ordinary commercial steel tubes.

The metal walls of the superheater elements are protected by the mass flow of the steam which should be such that the metal temperature will be within 50° F. of the steam temperature. As the superheater is brought nearer the furnace end of the boiler and becomes more exposed to higher gas temperatures, the mass flow of steam in the tubes must be increased. This means that less heating surface will be required, but unfortunately the pressure drop across the superheater must be increased to promote the necessary mass flow. Furthermore, where it is not possible to cool the superheater supports or spacers, their life will be limited if they are exposed to high temperatures unless they are made of good quality heat-resisting material, which is very expensive. In boilers operating with steam temperatures of 1,000–1,050° F. the heat absorption in the superheater may exceed 40 per cent. of the total absorption in the boiler, including the economiser. The superheater becomes very large and the corresponding gas temperature drop great. Therefore, in order to have an economical temperature difference between gas and steam at the cold end, the gas inlet of the superheater must be located in a zone of high gas temperature.

If a moderate superheat is required and the superheater is screened from the furnace by a thick bank of boiler tubes, heat will be transmitted by convection of the hot flue gases. A true convection superheater has a rising temperature-steam flow characteristic: see Fig. 13. Mass flow and temperature of the gas entering the superheater zone, as well as the steam flow from the boiler, increase with an increase in firing rate. As a change of condition of the gases has the greatest effect on heat transmission and as the increased steam velocity improves the rate of heat absorption, the steam temperature will rise as the firing rate increases. The amount of boiler surface that can be used as a screen between furnace and superheater will vary according to the type of furnace. As the furnace walls are more completely covered with water-cooled surface so will the gas temperatures throughout the boiler be lowered. Thus in a water-cooled boiler furnace the superheater can be arranged nearer the furnace than in a refractory-lined boiler furnace. Alternatively, the surface area of the superheater can be adjusted; approximately twice as much superheater surface is required for a boiler with a fully water-cooled surface as in the same boiler with a refractory furnace.

A convection type superheater from which 200 deg. F. of superheat is obtained in a coal-fired boiler will give only about 150 deg. F. superheat if

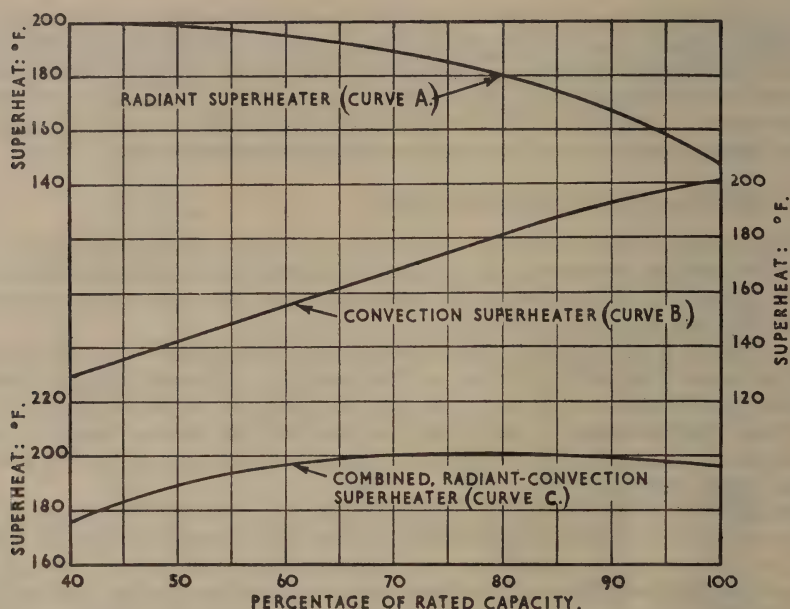


FIG. 13. Temperature/load characteristics of boiler superheaters.

the boiler is oil-fired, and considerably more than 200 deg. could be expected if the boiler were fired with a fuel such as blast furnace gas. A superheater so located that it is not entirely shielded from the furnace will be subject to both radiation and convection. From this superheater, steam may be expected at a constant temperature over a wide range of outputs. (See Fig. 13.)

Radiant heat superheaters may be situated on one or more furnace walls where heat is absorbed by direct radiation from the flames. Since the furnace temperature does not rise proportionately with the rate of steam production, a radiant superheater has a falling characteristic, i.e. the steam temperature drops as the steam output rises. The steam output temperature characteristic of a straight radiant superheater is shown as curve A in Fig. 13. Tubes located in furnace walls absorb heat at a high rate and in order to minimise tube failures the mass flow of the steam must be high, which can only be effected by a large pressure drop across the superheater. In Britain, true radiant superheaters of this type have been installed only in series with a convection superheater in order to stabilize the steam temperature with varying outputs.

Superheaters in modern high-pressure boilers are either horizontal or vertically pendant. The horizontal type is more difficult to support but there are advantages that can be claimed for this design. They are self-draining and, therefore, more suitable for boilers where the load may be intermittent and the boilers often banked. They are arranged so that the gases flow across the elements; a minimum of surface area is thus required.

It is more necessary that the cold end of a superheater operating with a low cold-end temperature difference should have a cross flow arrangement than at the gas inlet and where the temperature difference is so great that parallel flow is satisfactory and can often be used to advantage to reduce the pressure drop across the superheater.

When the gas temperature entering the superheater must be close to the fusion temperature of the ash it is customary to divide the superheater surface into two or more sections with wide tube spacing in the gas inlet section and

much closer spacing in the gas outlet section.

ECONOMISERS

The economiser, formerly regarded as a heat-recovery appliance placed in the path of the flue gases to abstract some of the heat that would otherwise be rejected to the chimney, may rather be regarded as an extension of the boiler heating surface added as a means of obtaining higher efficiency than if additional boiler heating surface were provided for the purpose.

An economiser must therefore be proportioned with the general plant conditions in mind if the maximum benefit is to be obtained from the minimum capital expenditure. The benefit increases with a rise in the cost of fuel. It has been estimated that about 1 per cent. of fuel costs can be saved for every 10° F. rise in the temperature of the boiler feed water so that, where very inefficient boiler plant is being considered, savings up to 15 and 20 per cent. can result. (see Fig. 14.)

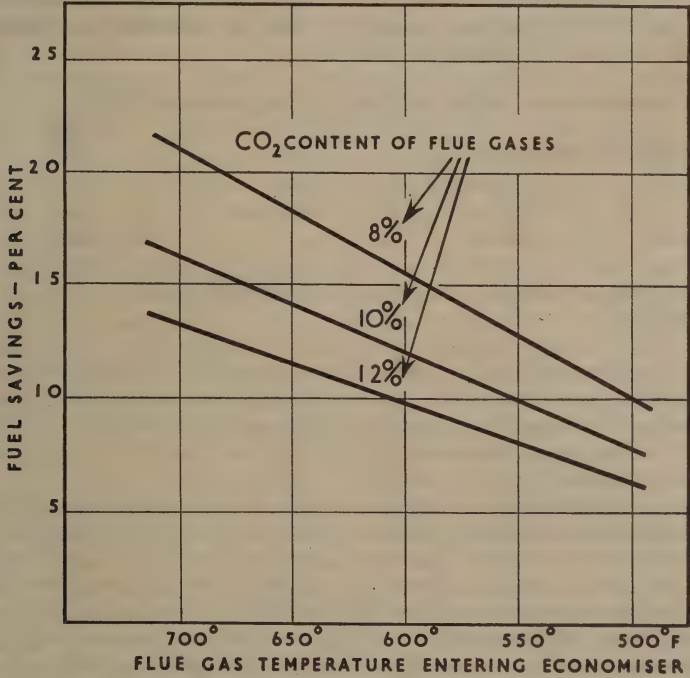


FIG. 14. Fuel savings from installing an economiser.

When more heat is available than can be used in increasing the sensible heat of the feed water, it may be necessary to use a “steaming” economiser or to reject the surplus heat to the chimney or pass it through an air heater. In most economisers, however, the feed water is not heated higher than to within 50 to 30 deg. F. of the temperature corresponding to the boiling point of the boiler water, thus preventing steam generation and subsequent water-hammer risks. An unconventional use of the economiser is to provide hot water for central heating.

ECONOMICS OF ECONOMISERS

The economic aspect of the installation can be regarded from two points of view. It can be considered that for a fixed evaporation the economiser provides a portion of the total heat added to the feed water to convert it into

steam; since this heat is obtained at virtually no cost it effects an appreciable saving in fuel. Alternatively, for a fixed weight of fuel burnt per hour, less heat is ejected to the chimney, more heat is converted into steam and more steam is generated.

The following simple examples illustrate these two points.

In a Lancashire boiler plant operating at 120 lb./sq. in. g. with no superheat and fed with water at 120° F., the total heat in 1 lb. of steam above that in the feed water is 1,193—(120—32), i.e. 1,105 B.t.u. If an economiser is installed and heats the feed water from 120° to 270° F. it adds approximately 150 B.t.u. to the feed water, and for the same hourly evaporation effects a

saving in fuel of $\frac{150 \times 100}{1,105}$ i.e. 13.6 per cent.

Suppose that a power station boiler generates 100,000 lb. of steam per hour and operates at 600 lb./sq. in. g. with a final superheated steam temperature of 850° F., the feed water leaving the turbine bleeder heater and entering the boiler unit at 300° F. Suppose, moreover, that by installing an economiser the feed water is heated from 300° to 450° F.:

	B.t.u./lb.
Total heat of steam at 600 lb./sq. in. g. superheated to 850° F.	1,435
Heat in feed water at 450° F.	430
„ „ „ „ 300° F.	270
Heat added in economiser	160
Heat in steam at 600 lb. and 850° F. with feed water at 300° F.	1,165

Without an economiser all this heat must be added in the boiler and superheater. With an economiser, 160 B.t.u. of this heat are added in the economiser, leaving 1,165—160, i.e. 1,005 B.t.u., to be added in the boiler and superheater. The evaporation will therefore be $100,000 \times 1,165/1,005$, i.e. 115,900 lb. per hour.

It is thus seen that without any increase in coal-handling plant, mechanical stoker, combustion chamber, boiler, superheater, forced draught fan, grit arrestor, gas-washing plant, chimney, ash-handling plant and boiler-house building, and for a small increase in induced draught fan power, the total evaporation has been increased by 15.9 per cent. This means that for practically the same capital expenditure 15.9 per cent. more steam is generated.

Several indirect advantages follow from installing economisers. Feeding of the boiler with water at a temperature near the boiling-point reduces the temperature differences in the boiler, prevents the formation of stagnant pockets of cold water and thus reduces greatly the temperature strains created in the pressure parts of the boiler and promotes better internal circulation.

Temporary fouling, due to impure feed water, may take place in the inside of the economiser tubes, which may necessitate shutting down the unit for internal cleaning. It is better that such deposits be in the economiser tubes whence they may be more readily removed than in the boiler tubes.

The temperatures experienced in the economiser not being as high as those in the boiler, the salts are sometimes deposited as a soft sludge and can be blown down through the economiser blow-down valve, instead of forming a hard scale on the inside of the boiler. Even where the unwanted hardness is deposited as a hard scale on the inside of the economiser tubes the economiser

can be by-passed for internal cleaning without putting the boiler out of operation. If the same feed water hardness were deposited inside the boiler it would probably necessitate putting the boiler out of commission for two or more weeks for internal scaling. Boiler feed water should be treated to minimise scale formation on all heat transmission surfaces.

Factors affecting Heat Absorption in Economisers. The amount of heat absorbed by an economiser depends upon the weight of flue gases available and their initial and final temperatures, upon the economiser heating surface provided, upon the mean temperature difference between the gases and the water and upon the overall heat transfer coefficient between the gases and the water.

The temperature of the gases after they have passed over all the boiler heating surface proper may be anything from 550° to $1,200^{\circ}$ F. (290° – 590° C.).

In any one boiler working under the conditions assumed during its design, the quantity of heat available in the flue gases is fixed. The aim of the economiser designer is to reduce the size and cost of the appliance to a practical minimum, which leaves only two variables—the mean temperature difference, and the heat transfer coefficient—available for modification. The mean temperature difference is a function of the gas and water temperatures, and is at a maximum when a counterflow of gas and water can be arranged, i.e. when the coldest water enters the economiser at the region where the coldest gases leave it. Counterflow, however, is not always possible, as, for instance, in some of the older forms of economiser; the designer must thus try to raise the heat transfer coefficient.

This coefficient is derived from three other coefficients: the coefficient for the heat flow from the gas to the external tube surface; that for the flow through the tube wall; and that for the flow from the economiser internal tube surface to the water inside it. The first coefficient (gas to external surface) depends principally upon the mass velocity and the temperature of the flue gases; the second is of relatively small importance in ordinary bare-tube economisers; and the third depends upon the mass flow of the water, the internal diameter of the tubes and the mean water temperature. The water coefficient is, in fact, so much larger in relation to the gas coefficient that it is usually sufficient to select a water velocity suitable for a given water pressure drop through the economiser, and ensure that turbulent flow will be maintained at the lowest expected boiler rating.

Extended Pipe Surface. Designers have thus been compelled to improve economiser performance by an increase in the gas coefficient, and this can be readily done by raising the gas velocity. The usefulness of this method, however, is restricted by the permissible cost of the extra fan power required (see Chapter 9, p. 190), though it can be extended to the limit by the addition of extra heat-absorbing surface, in the form of gills, etc., to the conventional form of bare economiser tube usually fitted.

The bare tube has disadvantages in that whether it is arranged in plain or staggered formation there are liable to be “dead” spaces behind the tube in the direction of the gas flow, and these spaces are untouched by the gases. Moreover, a certain amount of stratification is likely to occur (see Chapter 10) as a result of which layers of gas can pass right through the economiser without impinging upon more than a small proportion of the tubular heating surface.

The increased surface added to the bare tubes thus offers more surface for contact and increases the “scrubbing” action, but too much may defeat the purpose of the designer by causing an undue reduction in the temperature head available at the tube wall. It is in such circumstances that the second coefficient mentioned above—flow through the tube wall—assumes greater

importance in the computation of the overall heat transfer coefficient.

Types of Economiser. Turning now to a consideration of types of economiser in general use, it will be found that the plain-tube type is widely favoured in Lancashire boiler installations working under natural draught. The tubes are made of cast iron which is extremely resistant to the corrosive action of the flue gases, and their ends are pressed into top and bottom headers. The method of construction restricts the application of this type to pressures below 250 lb./sq. in., but an improved construction in which a number of the tubes in each section is positively secured to the headers by bolts allows of its use up to about 550 lb./sq. in.

Plain cast iron tubes are used where space is sufficient. The nest of economiser tubes is then arranged with the axes of the tubes vertical. Four, six, eight, ten or twelve tubes, machined at the ends and pressed hydraulically into top and bottom headers, are formed into a section. The sections are assembled in groups, the number varying according to the evaporation of the boiler plant and the duty required from the economiser. The standard lengths of tubes are 9, $11\frac{1}{2}$ and 13 feet.

The bare-tube design has the great advantage that the external surfaces can be continuously and directly cleaned by circular scrapers moving up and down the tubes, but if external corrosion is to be prevented, the entering feed water must be *at all times* at a temperature of at least 110° F. (43° C.) to eliminate "sweating". If corrosion is found to occur under these conditions the water inlet temperature should be raised by 20 degrees—i.e. to 130° F.

Gilled Tubes. A reduction in economiser size together with increased heat transmission can be obtained by casting circular gills on to the bare-tube walls, but at the higher pressures the cast iron tube is unsuitable. Steel tubes are then used; these have cast iron gilled sleeves shrunk on to them, the inner tube serving to withstand the pressure and the outer tube resisting any corrosive attack. Suitable spigot joints between the sleeve ends protect the inner tubes from external corrosion.

The ideal arrangement is for the gases to pass vertically downwards over such a group, and the water to pass vertically upwards, thus obtaining approximately contraflow heat exchange. The numbers of tubes and rows and their length are determined mainly by the total heating surface required and the draught loss permissible. It is usual to connect the tubes so that the water flows through all the tubes of the bottom row in parallel and then returns through all the tubes of the second row, then back through the third row, and so on. Thus the flow through the tubes of any one row is in parallel and the flow through the rows is in series. However, this arrangement can be changed to meet special circumstances, e.g. where a very low hydraulic loss through the economiser is desired, in which case the water passes through two rows in parallel.

Trouble with soot deposits, however, has necessitated modifications of the circular type of gill, and there are now available several forms of rectangular gills with "streamlined" surfaces designed to reduce draught losses to the minimum consistent with high heat transfer. It will be appreciated that tubes of the extended-surface type cannot be cleaned by mechanical scrapers while in service and must, therefore, be equipped with steam or compressed-air soot blowers. The blowers are operated at regular intervals and collect the soot in places convenient for removal.

Where weight is a major consideration, as in marine economisers, the gills are made from an alloy of aluminium. Since the coefficient of expansion of aluminium is greater than that of mild steel, provision must be made to keep each aluminium gill in intimate contact with the steel tube. This can be

effected by the insertion of a ring of special steel with a coefficient of expansion less than that of mild steel.

AIR PRE-HEATERS

The air pre-heater is an important auxiliary in modern boiler installations, transferring heat from the flue gases to the air fed to the furnace for combustion purposes.

The effects claimed from air pre-heating are as follows :

- (1) The recovery of heat from the flue gases reduces the heat loss from this source. It is claimed that every 30 to 35 deg. F. reduction of the flue gas temperature in this way results in a fuel saving of $1\frac{1}{4}$ – $1\frac{1}{2}$ per cent.
- (2) The flame temperature in the combustion space is raised with consequent greater rate of heat transfer by radiation (see Chapter 9), thus increasing the effective heat transfer and increasing the amount of steam made per boiler.
- (3) With higher flame temperature, the fuel can be burned with less excess air. In addition to the better utilization of heat (Chapter 6) there is also

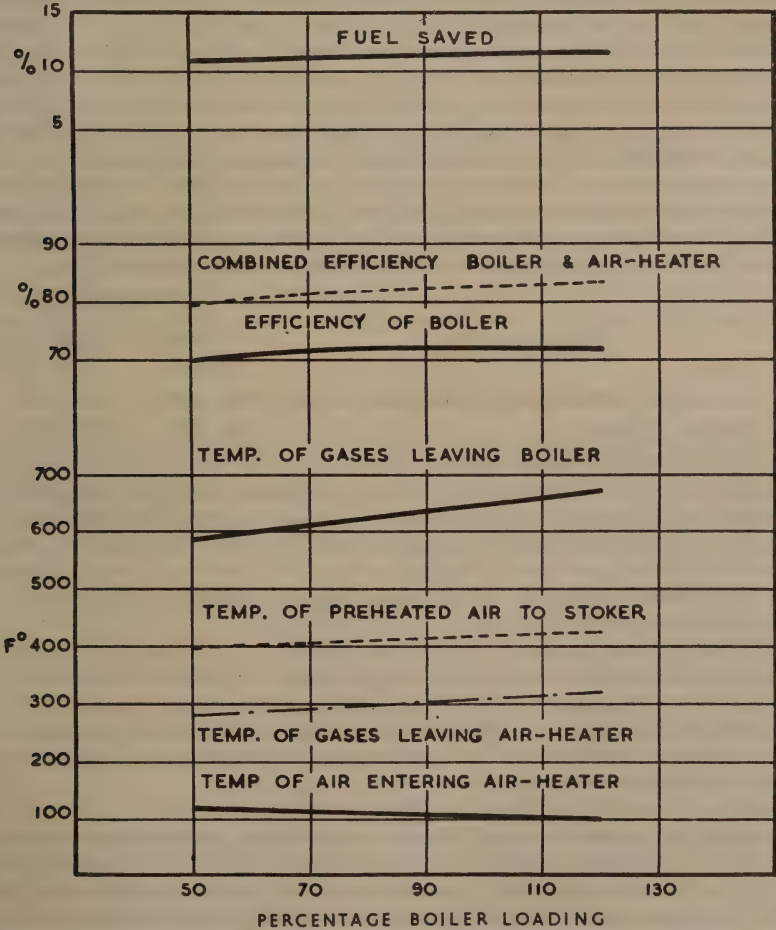


Fig. 15. Test results showing effect, on fuel consumption, of using Pre-heated Air.

from this cause a reduction in the power expended in producing draught.

- (4) Lower grades of fuel, or different grades, can be burned successfully with pre-heated air, that would not be effectively burned with cold air. Some coals can be burned satisfactorily only by heating the combustion air.

Fig. 15 indicates the advantageous effect on fuel consumption of using pre-heated air.

Types of Air Pre-heater. Pre-heaters are either regenerative or recuperative, and in general principle are similar to the regenerators and recuperators used in furnace work (Chapter 19).

With recuperative heaters the gases pass on one side and the air on the other side of the tube or plate wall, the heat transfer taking place through the plate. All tubular and plate heaters come within this group.

Recuperative heaters are more economic on small installations and where a small proportion of the available heat has to be recovered, but deposits on the plates affect the rate of heat transfer.

Regenerative heaters operate by passing hot flue gases and cold air alternately over the heating elements. Heat is picked up by the elements from the gases and in the next stage of the cycle is transferred to the air. Only one heater of this type is marketed in Britain for use with steam boilers. In this apparatus, the element plates are assembled in a cylindrical housing, which is rotated slowly so that the elements pass alternately through the flue gases and air during each revolution. The elements are heated by the gases and then cooled by the air ; thus the heat transfer is continuous.

Temperature Limits. With each method of burning fuel in a boiler furnace there is a limit to the temperature of the combustion air, and if this limit is exceeded the maintenance charges on stokers, burners or furnace parts increase rapidly. The maximum hot-air temperatures are approximately:

<i>Method of firing</i>	<i>Temperature</i>	
	<i>°F.</i> (<i>approx.</i>)	<i>°C.</i> (<i>approx.</i>)
Hand	150-200	65- 95
Sprinkler and chain-grate stokers ..	250-300	120-150
Retort stokers	350-400	175-200
Pulverized coal or oil firing	Up to 600	Up to 315

On the gas side of an air heater the maximum entering temperature is restricted to 750°-800° F. (400°-430° C.), i.e. the temperature that mild steel will safely withstand should the air flow cease. Beyond this limit it would be necessary to introduce special designs or special operating precautions, or to make the heater elements of high-temperature resisting alloy steels, thus greatly increasing the cost.

Many air heater troubles result from working with too low an exit gas temperature or too low an air inlet temperature, or both. The corrosion difficulty has been explained when dealing with economisers. In addition, the deposition of moisture will cause dust to stick to the heating surfaces, which impairs heat transmission. The prevention of condensation within an air heater is therefore imperative.

The Prevention of Condensation. With recuperative heaters the most satisfactory method of maintaining the requisite element plate temperature at the air inlet end is to return some of the heated air to the forced draught fan inlet. Thus the temperature is raised to just above that at which condensation would occur in the flue gases. As the temperature of the element plates cannot fall below the entering air temperature, this method has successfully overcome most corrosion and deposit troubles. An amount equivalent to 30 or 40 per

cent., or even more, of the air passing through the heater may have to be re-circulated in this manner to ensure that the air temperature at the heater inlet is at the required figure, usually between 115° and 130° F., according to fuel and combustion conditions.

The makers of the regenerative heater claim that re-circulation of air is not necessary in their design. Because of its rotation and of the absence of sections with a cross-flow of gas and air, cool spots caused by uneven air and gas distribution at the air inlet end do not occur, and all the element plates are subjected to the same minimum temperature conditions.

In boilers of the Lancashire, Economic, Scotch marine types, the flue gas temperature at the heater outlet should not at any time during operation fall below 280°–300° F. (140°–150° C.). In water-tube boilers, which are usually larger and obtain their air supply from above the boilers where the air temperature is already high, combustion conditions are in general steadier and more closely controlled, so that gas temperatures down to 250° F. (120° C.) may be permitted when the fuel and combustion conditions are favourable.

The most satisfactory means of controlling the gas outlet temperature above the required limit at reduced loads is to provide air by-pass ducts and dampers. By opening the air by-passes, some air is short-circuited past the heater, less heat is taken from the flue gases and the gases then leave the heater at a higher temperature. The heater elements are thus maintained at the proper temperature.

For satisfactory control of an air heater it is usually necessary to provide a gas by-pass having a tightly shutting damper, isolating dampers to prevent gas flow through the heater during starting-up, banked-fire and shutting-down conditions, and air by-pass ducts with regulating dampers. On recuperative heaters, air re-circulating ducts and regulating dampers are advisable. A forced draught fan should be installed. Many air heaters are designed for a low draught loss on the gas side so that they can work in conjunction with chimney draught only, but it is usually found advantageous to fit an induced draught fan.

SOOT-BLOWERS AND WATER LANCES

The combustion gases from all boiler furnaces contain a proportion of dust and grit which will vary according to the type of firing, furnace design, boiler load and operating conditions. Soot-blowers are used to keep the boiler surfaces free from deposits of dust and grit which would otherwise reduce the rate of heat transmission in the boiler, lowering the boiler efficiency, reducing availability.

It has been well established that regular soot-blowing is essential if a high thermal efficiency is to be maintained in a water-tube boiler over any appreciable length of time. Thus provision is made for soot-blowing in the basic design of modern water-tube boilers, the disposition of the tubes in each bank being so arranged as to come within the effective range of the soot-blowers. These may vary from eight to ten tubes deep, and this applies to boiler, superheater and economiser heating surfaces which are arranged accordingly.

Grit is particularly troublesome in the high temperature zones of water tube boilers, i.e. before and including the superheater. If it is allowed to remain it can form a hard bonded deposit which is difficult to remove either manually when the boiler is off load or by soot-blowing. If, in addition, deposits are allowed to build-up (known as "bird nesting") this would so restrict the flow of gases through the boiler that it would soon be unable to carry the required load and would have to be taken out of service for cleaning. Once the spaces between tubes have become bridged with solid deposits, there is no known

method of clearing a tube nest in the high temperature zone while the boiler is on load. If the deposits are such that soot-blowing has no effect they may be removed by means of water lances. If water lances are not effective the boiler must be taken out of service.

It is, therefore, essential that soot-blowing operations conform to a regular schedule, say once per shift; the minimum *duration* for effective soot-blowing will be found only by experience.

The deposits in shell boilers, and after the superheater in water-tube boilers, usually remain in the form of dust and are more easily removed by blowers. These deposits usually settle where they are not affected by the gas stream; and there will be a limit to the amount deposited, as any excess will generally be carried off in the gas stream. Nevertheless, the boiler efficiency may be seriously affected by impairing the heat transmission in the boiler. For example, the temperature of the flue gases from a hand-fired Lancashire boiler rose by over 200 deg. F. after 40 days operation without soot-blowers; a rise in temperature corresponding to a loss of efficiency of about seven per cent. In this particular boiler the steam consumption of the soot-blowers is only 0.3 per cent. of the boiler output. This is small compared with the potential saving in fuel, and even allowing for increased maintenance costs, the installation of soot-blowers would be worth while financially. Although this is a typical case, each plant must be examined individually and any rise in flue gas temperature should be noted after the boiler has been in commission for a period. It will then be possible to decide if soot-blowers are necessary.

Soot-blowers have been developed to suit the requirements of most boiler plants. They may be operated manually, though in larger boilers it is usually arranged to be done automatically. Where deposits are liable to become hard, single-nozzle blowers are essential. These are usually retractable when not in use to protect the heads from exposure to high temperatures. Softer deposits may be removed by multi-jet blowers. These may or may not be retractable and a selection can be made from nozzles which use a larger number of small jets to nozzles containing a few large jets.

To provide the necessary momentum and to minimise nozzle wear, soot-blowers are usually supplied with saturated steam, and to be effective single-nozzle blowers require a minimum pressure of 200 lb. per sq. in.; the minimum pressure for multi-jet nozzles varies from 80 to 150 lb. per sq. in., depending on the size of the jets. Soot-blowers may be air-operated but so far these are more costly in installation and operation and are usually no more effective than steam soot-blowers.

It is of vital importance that the soot-blowing equipment be maintained in good condition, that the blowers be properly set and adjusted to traverse the correct arc, and that the specified steam pressure be maintained at the blower head while the blower is in operation.

The operation of soot-blowers must be properly supervised, particularly where they are operated by hand. The pipework for the soot-blower system must be so arranged as to ensure adequate drainage and warming, as moisture in the pipelines not only erodes and cracks the nozzles of the blowers, but also tends to erode the heating surfaces nearest to the nozzles. Careful attention to drainage and warming will, therefore, help to obviate excessive maintenance and unsatisfactory soot-blowing. For illustrations of soot-blowers see Figs. 15-17, Chapter 11.

Water Lancing should be considered as a process complementary to soot-blowing, as it is generally found that the hardest deposits having the greatest resistance to the action of soot-blowers are those that can be most readily removed by water lancing. Water lancing the softer and more bulky deposits

is not always successful.

The essence of this process is the sudden chilling of the bonded deposits on the tubes. The deposits should be alternately chilled and allowed to heat up while the plant is in service. The thermal stresses set up in the deposit cause it to loosen and fall off, sometimes in fairly large pieces. If the pieces are too large to fall clear of the tube bank there is little point in water lancing; the frequency of water lancing should, therefore, be so adjusted that no appreciable thickness of deposit is allowed to form. Once a fortnight is usually sufficient. A tube nest should, of course, always be water-lanced progressively from underneath to allow the deposit to drop away freely.

Water lances, which are usually portable, are constructed of mild steam tubing of various bores from $\frac{1}{2}$ inch to 1 inch. It is often convenient to bend the end of the lance at 45° so that the jet may be easily directed on to the tubes. A small bore nozzle, preferably machined from the solid, is screwed on to the end of the pipe. Clean water from any convenient supply may be used, preferably at a pressure of 40–60 lb./sq. inch. It is important that the scope of the jet should be capable of accurate control so as to prevent water being sprayed on to supports or refractories, and particularly on to expanded tube joints.

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- The British Standards Institution has issued many British Standards and Codes of Practice relating to boiler fittings and auxiliary plant. Among these the following are of special relevance:
- B.S. 848. Testing of fans for general purposes (excluding mine fans).
- B.S. 994. Centrifugal and axial flow pump specifications and data required for estimates and orders.
- B.S. 1712. Cast iron economisers with extended surface horizontal tubes.
- B.S. 1713. Cast iron economisers with pressed socket joints.

CHAPTER 16

WATER TREATMENT

THE PRINCIPAL uses of water in industry are :

- (1) For steam raising, the steam being used for electrical or mechanical power generation, heating, or chemical reaction.
- (2) As a cooling medium.
- (3) For hot water supply and hot water heating systems.
- (4) As a solvent and reactant in chemical processes.
- (5) As a suspending medium in processes of mechanical separation such as coal washing.
- (6) For drinking.
- (7) For laundering, washing and general domestic purposes.

The last four items are beyond the scope of this book although some of the principles and methods of water treatment discussed are applicable to those waters in appropriate instances. The main topic discussed in this chapter therefore is feedwater conditioning for boiler plant but the treatment of water for cooling purposes and hot water heating systems is also considered briefly.

IMPURITIES IN NATURAL WATERS

All water supplies contain impurities in the form of dissolved gases, and solids in solution or suspension, and although a "bad" water may contain less than 0.05 per cent. of dissolved solids, the cumulative effect of these is considerable. Most industrial water supplies require treatment for one or other of the purposes mentioned above. Such treatment consists essentially in either removing objectionable constituents or at least reducing their concentration to a level at which they are relatively innocuous, or the addition of substances which suppress the undesirable effects.

The quantities of substances present in waters used for steam raising may be sufficiently high to be stated in percentages or so small as to be stated in grains per gallon or even in parts per million, generally written : p.p.m.

The common impurities in natural water supplies are:

Dissolved gases—always present

Carbon dioxide (CO_2) and oxygen (O_2), up to about 90 p.p.m. and 12 p.p.m. respectively, and occasionally hydrogen sulphide (H_2S) up to 4 p.p.m. and ammonia (NH_3).

Suspended solids—sometimes present

Mineral and vegetable detritus such as sand, silt, and decaying plants in varying amounts.

Dissolved organic substances—sometimes present

Materials such as peaty acids and complex coloured substances extracted from soil or plants and proteins.

Living organisms—always present to some extent

Natural water bacteria, soil bacteria and sewage bacteria. Algae, etc.

Dissolved salts—always present

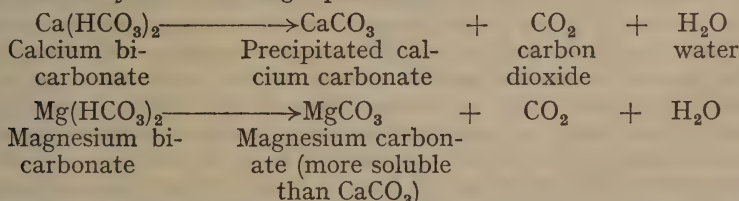
The bicarbonates, chlorides, sulphates and nitrates of calcium, magnesium and sodium in varying proportions, together with silica, and sometimes small amounts of iron, manganese and aluminium.

The most important of these are the calcium (Ca) and magnesium (Mg) salts since the cations Ca and Mg are the cause of *hardness* in water, and most of the scales and deposits formed from natural waters in boiler plant and cooling plant are compounds of calcium and magnesium. (See Ion Exchange below.)

The calcium and magnesium salts may be divided into two groups:

- (1) The bicarbonates $\text{Ca}(\text{HCO}_3)_2$ and $\text{Mg}(\text{HCO}_3)_2$ which, because they are easily decomposed by heat, cause *temporary hardness*, also known as alkaline hardness or carbonate hardness.
- (2) The sulphates, chlorides and nitrates CaCl_2 , MgCl_2 , CaSO_4 , MgSO_4 , $\text{Ca}(\text{NO}_3)_2$ and $\text{Mg}(\text{NO}_3)_2$ which are not decomposed by boiling and cause *permanent hardness* also called non-carbonate or non-alkaline hardness. The nitrates are normally present in very small quantities.

The decomposition of temporary hardness substances by heat may be represented by the following equations:



It should be noted that the CO_2 liberated will give an acid steam condensate.

TYPES OF WATER

The chemical composition of water supplies varies widely, but in Britain we can distinguish according to source three classes of water, each of which has characteristic quantities.

- (a) Surface drainage from upland areas, i.e. streams, lakes and reservoirs situated in moorland type of country.
- (b) Surface drainage from lowland areas, i.e. agricultural countryside.
- (c) Underground supplies, i.e. deep springs and wells and water from the lower measures of coal pits.

Moorland waters are usually fairly constant in composition, and are clear except perhaps in times of spate. They may be coloured brown, and are often slightly acid, due to dissolved CO_2 or to weak organic acids derived from peaty material, which makes them corrosive, and, although the hardness ($\text{Ca} + \text{Mg}$) is low, they form sufficient scale in boilers to justify treatment. A small amount of iron is often present, probably in combination with the organic matter, and as a result of the activities of certain strains of iron bacteria the iron may be abstracted and deposited on the walls of pipes as hydrated oxide.

Lowland surface waters are not often coloured, but may contain fine suspensions of mud which settle only after prolonged periods unless assisted by coagulants. Their composition can vary widely as a result of heavy rainfall, and the hardness, which is present as both temporary and permanent hardness, is usually high enough to form serious amounts of scale and deposit in boilers, economisers, and cooling plant. Rivers and canals may be contaminated by trade or sewage effluents which can interfere with the normal methods of softening.

Deep well waters are usually fairly constant in composition, though occasionally slow changes may take place as a result of contamination by other waters percolating through faults in the strata. When freshly drawn they are often "water-white", clear and sparkling, but sometimes a brown opalescence develops on exposure to air, for which small amounts of iron are responsible.

This iron is probably in the ferrous condition and is deposited as hydrated ferric oxide by the combined effects of oxidation and the loss of CO_2 . Such waters usually contain traces of sulphuretted hydrogen easily detectable by odour, and no dissolved oxygen; hence the slight delay in the precipitation while oxygen is being absorbed from the atmosphere. Iron bacteria can also exist in these waters, and the iron may than be deposited on the walls of pipes by their action as well as by air oxidation.

The hardness is often entirely in the form of temporary hardness and sodium bicarbonate may be present as well. The silica content is usually high, e.g. about 15–20 p.p.m.

THE EFFECTS OF IMPURITIES IN WATER

The most objectionable effect of using raw water in a boiler is the deposition of hard adherent scales on the heating surfaces. These have a low thermal conductivity estimated at between 8 and 24 B.t.u./sq. ft. hr. deg. F. inch thickness, so that the metal is not properly cooled and its temperature rises to the point at which it softens, bulges and splits under pressure, with dangerous results. The parts of the heating surface most sensitive to this effect are water tubes exposed to radiant heat, or furnace tubes of shell boilers, where rates of heat transfer and water evaporation are high. In tubes receiving heat by convection and conduction greater thickness of scale can be tolerated before failure takes place. The direct loss of heat or waste of fuel caused by scale has been estimated at about 2 per cent. or even less in water-tube boilers, but may be up to 5 or 6 per cent. in smoke-tube boilers where heating surfaces are short. The more important losses are the cost of repairs, interrupted service of plant during mechanical de-scaling, and fuel required to start up another boiler in the event of tube failure.

Many waters also deposit solids in the form of soft scale and sludge, at and below boiler working temperatures. These deposits are found in cooling plant, feedwater heaters and economisers as well as in boilers. A certain amount of sludge can be tolerated in a shell boiler where it settles into the cooler parts, from which it can be removed by opening the blow-down cock momentarily a few times each day, but if the accumulation is not controlled in this way sludge may stick to the heating surfaces in a soft layer, which retards heat flow even if it does not cause failure. This is particularly objectionable in Economic and loco-type boilers, because of the difficulty of cleaning between the tubes. The accumulation of more than small quantities of sludge in water-tube boilers should be avoided, because it can accentuate the formation of foam in the boiler drum and carry-over of boiler water into the steam, and because severe corrosion can take place underneath piles of sludge in tubes in which the circulation is sluggish. There are numerous examples of this type of corrosion in boilers working at higher pressures, above 400 lb./sq. in.

The gases carbon dioxide and oxygen which are dissolved in water, together with the carbon dioxide which is liberated when waters containing bicarbonates are heated, can cause corrosion in economisers and boilers, and since they pass out with the steam they reappear in condensate, which is therefore corrosive. Lastly, salts and suspended solids in boiler water can under certain conditions be carried out of the boiler in the steam and deposit in superheaters, steam mains, and turbines.

The aims of water treatment are, therefore, to prevent the formation of hard scale in the boiler and of other deposits in ancillary (pre-boiler) equipment such as economisers—to control the amount of sludge in the boiler, to reduce or eliminate corrosion caused by salts in the boiler water or carbon dioxide in steam, and to avoid the contamination of steam by salts in the boiler water.

SCALE

Chemical analysis has shown that the chief constituents of hard boiler scales are calcium sulphate (CaSO_4) and calcium and magnesium silicates, often mixed with calcium carbonate (CaCO_3) and magnesium hydroxide ($\text{Mg}(\text{OH})_2$), and that soft deposits or sludges are composed of CaCO_3 and $\text{Mg}(\text{OH})_2$, with only small quantities of other constituents. Table 1 shows some examples of hard boiler scales.

TABLE 1
COMPOSITION OF TYPICAL HARD BOILER SCALES

	<i>Sulphate scale</i>	<i>Carbonate and sulphate scale</i>	<i>Carbonate and silicate scale</i>
	<i>Per cent.</i>	<i>Per cent.</i>	<i>Per cent.</i>
CaCO_3	6.03	45.6	37.4
$\text{Mg}(\text{OH})_2$	6.32	9.8	2.52
CaSO_4	83.23	34.7	1.65
SiO_2	1.02	7.4	29.2
Calcium silicate			20.6
$\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3$	1.56	1.9	2.26
Water and organic matter ..	1.54	0.6	2.65
	99.7	100.0	96.28

Scales consisting essentially of calcium sulphate are the most common. Scales containing silica are less common but very thin layers can cause tube failures. They are complex substances as compared with calcium sulphate, and the conditions of formation and prevention are not known precisely. Experience seems to show, however, that in moderately rated boilers at pressures up to 900 lb./sq. in. the use of phosphates in feedwater conditioning has usually proved successful in preventing the formation of calcium and magnesium silicate scales in the boiler.

Scales consisting almost entirely of silica have been formed in water-wall tubes of some modern highly rated boilers operating at 600 lb./sq. in. and above, in which a large part of the heat transfer is by radiation, and in such cases it has been necessary to apply special treatment to reduce the silica content of the feedwater, or to diminish its concentration in the boiler water by increasing the blow-down. There does not appear to have been any occurrence of this type of scale in Britain.

Analcite scales, which are sodium aluminium silicates and contain no calcium or magnesium, sometimes form as a result of using excessive quantities of aluminium salts in clarification or softening; in such cases these processes should be more carefully controlled.

All the scales and sludges except analcite contain calcium and magnesium; the logical first step in feedwater treatment is, therefore, the removal of these ions from solution by a standard softening process. This is the procedure usually recommended when the water is very hard, or is to be fed to boilers working at pressures above about 250 lb./sq. in.

WATER SOFTENING PROCESSES

There are three methods of softening water for boiler feed:

- (1) Precipitation processes, in which chemicals are added to precipitate calcium and magnesium as compounds of low solubility. The lime-soda process is typical of this class, but other precipitating agents such as caustic soda and sodium phosphate can be used when the composition of the raw water permits.
- (2) Ion-exchange processes in which the hardness is removed as the water

passes through a bed of natural zeolite, or synthetic resin and without the formation of any precipitate. The well-known base-exchange softening process is an example.

- (3) Water which is essentially free from dissolved salts can be prepared by evaporation and condensing the steam, or by demineralization which is a two-stage ion-exchange process.

A brief and very general description of these processes is given below, but it must be emphasized that the choice of process depends on the composition of the raw water and the purposes for which the treated water is required, and a decision on such points is best worked out with the help of an expert.

PRECIPITATION PROCESSES

Lime-soda

In the lime-soda or lime-soda/sodium-aluminate or other coagulant process, calcium and magnesium are precipitated as compounds of very low solubility, namely CaCO_3 and $\text{Mg}(\text{OH})_2$, by the addition of hydrated lime and sodium carbonate, or by hydrated lime alone when the raw water contains sodium bicarbonate. The amounts of chemicals added must be in proportion to the Ca and Mg present in the water and will therefore require adjustment if the composition of the water changes. The process can be worked hot ($70\text{--}90^\circ\text{C.}$) or cold, the former usually giving better clarity and hardness removal, particularly with turbid waters or waters containing organic matter. The amount of sodium aluminate required for coagulation of the magnesium hydroxide is of the order of 10 p.p.m. in hot softening and 20 p.p.m. in the cold, irrespective of the amount of hardness to be removed; it is, however, used only when the raw water contains appreciable amounts of magnesium salts. A small amount of residual hardness is always present in the treated water and amounts to about 10–15 p.p.m. CaCO_3 in the hot process and 15–25 p.p.m. in the cold. Aluminium sulphate and modified (activated) silicate may also be used as coagulants.

The plant comprises stock tanks for preparing and storing the mixture of reagents, usually as of a thin slurry containing $\frac{1}{2}$ to 1 lb. chemicals per gallon of water; an apparatus for adding measured quantities of this slurry to the raw water in proportion to its rate of flow; a means of mixing chemicals and water intimately; a settling tank with a retention time of one hour (for hot softening) or three hours (for cold); and filters. The settled precipitates are removed as a slurry containing about 5 per cent. of solids, which is run to waste.

Various types of reaction tank designed to speed up the reaction rate in precipitation softening carried out in the cold have been developed in the last ten years or so. The general principle is to introduce pre-formed precipitate—calcium carbonate and magnesium hydroxide—to the water at the point where the softening chemicals are added. This encourages the precipitation of fresh solid on the existing particles, instead of forming new particles. The sludge from this type of plant will contain 15–25 per cent. of solids.

Phosphate Softening

The solubility of calcium phosphate is less than that of CaCO_3 ; a precipitation process using sodium phosphates instead of sodium carbonate should thus give a greater removal of hardness. This is in fact the case, but phosphates are expensive, and their use is limited in practice to a second stage of softening at high temperatures for the special purpose of treating water for use in boilers working in the higher pressure range, i.e. above 500 lb./sq. in.

The procedure is to submit the water to a hot lime-soda or lime-soda/sodium-aluminate softening at $70\text{--}90^\circ\text{C.}$, and then to pass the treated water containing about 10–15 p.p.m. of residual hardness to a similar plant in which sodium

phosphate is added in sufficient amount to precipitate the residual calcium hardness. The water leaving the lime-soda section should contain enough caustic alkali to precipitate magnesium as $\text{Mg}(\text{OH})_2$. After settling, the water is passed through filters, and the hardness should be reduced to about 2 p.p.m.

ION EXCHANGE PROCESSES

The atoms of calcium and magnesium present throughout the water before treatment are termed, by the chemist, *ions*, as are atoms of chlorine (in chlorides), the sulphate group SO_4 , the carbonate group CO_3 , and other atoms of elements and groups of elements. The calcium and magnesium (as well as sodium, potassium, etc.) are in this context termed *cations* and the chlorine, sulphate group, carbonate group (etc.) are termed *anions*.

Ion exchange processes are based on properties possessed by certain minerals known as zeolites which are essentially sodium aluminium silicates. When water containing hardness is allowed to percolate through a bed of suitably graded zeolite nearly all the calcium and magnesium ions are replaced by sodium and the water is thus softened. Eventually all the sodium in the zeolite is used up and the bed consists essentially of calcium and magnesium zeolite, but this can be reconverted into the sodium zeolite by treatment with a strong solution of brine (NaCl).

Many other cations, e.g. potassium, barium, strontium, and iron, can be exchanged for sodium in the same way to varying extents; and sodium in its turn can be displaced by ammonium and hydrogen ions.

Synthetic zeolites have been made which are more efficient in softening than the natural minerals, but these materials have been surpassed during the last ten years by substances of quite a different class. The first of these were products obtained by partial dehydration and sulphonation of coal, and were followed by the discovery of Holmes and Adams that resins made by the condensation of phenols and formaldehyde also have good exchange properties. Other types of resins having similar properties have more recently been developed.

These processes work best with clean water. Suspended solids in the raw water should be removed by filtration, using coagulants if necessary, otherwise they will clog the pores of the exchange material and reduce its exchange capacity. There are also working losses due to abrasion and carry-over of fine material, so that some fresh material must be added after a year or two, as make up. These losses vary according to working conditions, and the plant suppliers should be consulted for estimates of losses in any given case.

Base Exchange Softening (Cation Exchange)

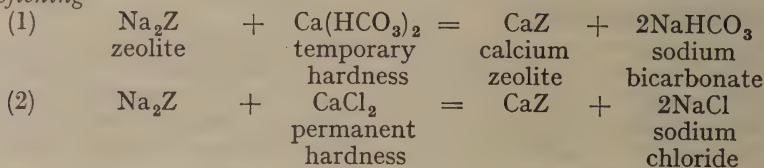
This process consists of a cycle of operations in which the raw water is pumped through a bed of exchange material until tests on the issuing water show that the bed is failing to remove calcium and magnesium ions completely. At this point the flow of water is shut off, or diverted to an adjoining fresh bed of material after a short backwash with water, and a strong solution of brine (5–10 per cent. NaCl) is pumped or syphoned through the exhausted bed for some 5 or 10 minutes.

During this period the relatively high concentration of sodium ions in the brine replaces the calcium and magnesium ions in the zeolite and re-forms the sodium zeolite. The calcium and magnesium ions pass into solution and out to waste when the brine is run off, and the regenerated bed is then washed free from brine generally by an upward flow of water before more raw water is admitted. The full cycle of operations is Softening, Backwashing, Regeneration, Rinsing, Softening, and the plant is usually divided into several units so that the regeneration and washing stages do not interfere with the continuity of the supply of softened water. In some plants all these operations can be set

in motion automatically after a measured volume of water has been softened.

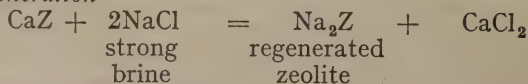
The changes may be expressed by the following simple equations in which Z represents the anion of the base exchange material :

Softening



Magnesium salts behave in the same way as those of calcium.

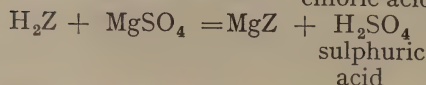
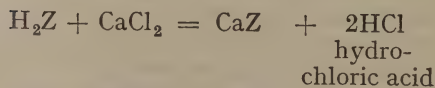
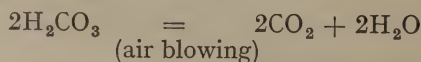
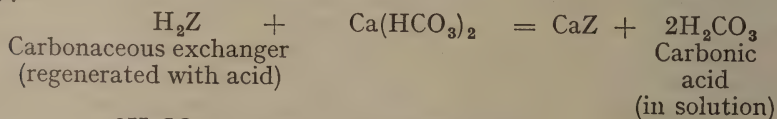
Regeneration



This method of softening is not really suitable for waters having a high temporary hardness that are to be used as boiler feed, because the temporary hardness (calcium and magnesium bicarbonates) is converted to sodium bicarbonate which is decomposed in the boiler to CO_2 and caustic soda, and for reasons given in the section headed "Caustic embrittlement" a large amount of caustic soda in boiler water is objectionable. CO_2 in the steam can cause corrosion.

Hydrogen Ion (Cation) Exchange

The most important difference between the zeolites and the carbonaceous or resin exchange materials, is that when the latter are regenerated with acids they can exchange hydrogen ions for sodium, calcium and magnesium ions, so that all the salts in the water passing through the bed are converted to the corresponding acids. Thus bicarbonate becomes carbonic acid which can be decomposed into CO_2 and water by air blowing, whereas chloride, sulphate and nitrate remain as mineral acids. The equations representing these changes are :



The treated water is not suitable for use at this stage because it is corrosive, but, as explained in the next section, the acidity can be neutralized. The plant must, of course, be lined to protect it from attack by acid.

Blended Acid and Base Exchange

If part of the water is passed through a hydrogen exchange unit and the remainder through a base exchange unit, the two treated waters may be blended, with the result that not only is the mixture softened but the bicarbonates are destroyed by conversion into CO_2 , which is removed by aeration.

A similar result is achieved by regenerating a carbonaceous zeolite with a

mixture of acid and salt, but complications ensue if the composition of the raw water is subject to sudden and wide variation, since the proportions of acid and salt must be altered to correspond with the proportions of bicarbonate and permanent hardness.

Waters containing calcium temporary hardness can be treated by a combined process, in which the bicarbonates are removed by treatment with lime and passing this treated water through a base exchange plant.

De-mineralization (de-ionization)—Cation Exchange + Anion Exchange

Holmes and Adams also discovered that resins made from formaldehyde and metaphenylene diamine or similar substances have the property of absorbing acids, and by combining this property with that of hydrogen exchange they were able to produce water nearly as pure as distilled water.

This process is achieved in two steps. The water is first passed through a carbonaceous zeolite or synthetic resin which has been regenerated with acid, and the effluent then passes through a bed of acid-absorbing resin which has been regenerated with caustic soda or sodium carbonate, the acids formed in the first stage being absorbed in the second. Plants working on this principle are in operation producing make-up water for high pressure boilers or other purposes, and it is found that as a rule the salts are reduced to about 20 p.p.m. but silica is not removed at all, so that the total solids in the treated water will vary between about 15 and 20 p.p.m. The CO_2 produced in the first stage from the bicarbonates is removed by air blowing. Apart from its silica content, the water from these plants is probably as pure as would be obtained from the standard commercial types of evaporator. Silica can be removed in this process by passing the water through a third vessel containing a strongly basic resin, which can reduce it to under 0.05 p.p.m., the total solids then being 0.5 p.p.m. or less.

Mixed Bed De-ionization

The introduction of "bead resins", the individual particles of which are approximately spherical, has led to the development of "mixed-bed" de-ionization. In this method the cation and anion exchangers are mixed during the treatment process, but are separated by an upward flow of water before the caustic soda and acid regenerating solutions are applied. After regeneration and rinsing, the materials are re-mixed by means of compressed air. The intermingling of the two types of material during treatment enables very efficient de-ionization to be carried out and, as the anionic resin is strongly basic, silica is removed.

Mixed-bed treatment sometimes follows a conventional two-bed de-ionization process as a final finishing stage. Direct treatment of a hard water containing a large amount of bicarbonate in a mixed bed unit is more expensive than in a two-bed plant, where the carbon dioxide produced from the bicarbonates by hydrogen exchange is removed in a degassing tower.

Evaporation

Evaporation is widely employed to provide make-up feed water for boiler plants in which a large proportion of condensate is recoverable from process or turbines and the amount of fresh make-up is small. The raw water to be evaporated should be softened or otherwise treated to prevent scale formation and liberation of CO_2 in the evaporator. The evaporators may be single or multiple-effect though it is not usual to employ more than three effects.

The steam for heating may be waste low grade steam or be taken from low pressure boilers, or, as in many power stations, tapped off from one of the turbine stages. The heat in the distillate vapour is recoverable by condensing in feed water heaters or de-aerating heaters. To secure the most economical

TABLE 2
EFFECTS OF WATER TREATMENT ON COMPOSITION OF TREATED WATER (APPROXIMATE FIGURES)

	Parts per million										T.D.S. HCO ₃ calculated as CO ₃	Hardness as CaCO ₃ Total. Temp'y	pH approx.		
	Cations			Anions											
	Ca	Mg	Na	HCO ₃	CO ₃	OH	Cl	SO ₄	NO ₃	SiO ₂					
EFFECTS OF SOFTENING ON SURFACE WATER FROM AGRICULTURAL AREA															
Raw water	63	18	25	159	—	—	43	79	16	10	332	232	130	7.5	
Hot lime-soda/sodium-aluminate(above70°C)	2	1	109	—	36	10	43	79	16	6	301	10	—	10	
Base exchange (cold water)	1	0.5	129	159	—	—	43	79	16	10	357	5	—	6.5-7.5	
Acid exchange and base exchange—blended (cold water)	1	0.5	74	12	—	—	43	79	16	10	230	5	—	7	
De-mineralization (cold water)	nil or very small	—	—	—	—	—	—	—	—	10	15-20	nil or very small	—	7	
Distillation (hot or cold)											10			5-6.5	
EFFECTS OF SOFTENING ON DEEP WELL WATER															
Raw water	48	21	72	348	—	—	48	10	—	17	387	205	205	7	
Hotlime-soda/sodium-aluminate(above70°C)	2	1	72	—	36	10	48	10	—	12	191	10	—	10	
Base exchange (cold water)	1	0.5	164	348	—	—	48	10	—	17	411	5	—	6.5-7	
Acid exchange and base exchange—blended (cold water)	1	0.5	38	12	—	—	48	10	—	17	120	5	—	7	
De-mineralization (cold water)	nil or very small	—	—	—	—	—	—	—	—	17	22-27	nil or very small	—	5-6.5	
EFFECTS OF SOFTENING TREATMENT ON MOORLAND WATER															
Raw water	7	5	8	15	—	—	10	31	—	4-8	76	40	12	6.5-7	
Hot lime-soda/sodium-aluminate(above70°C)				Unsuitable	because raw water hardness is too low for effective precipitation.										
Base exchange (cold water)	1	0.4	25	15	—	—	10	31	—	4-8	82	5	—	6.5-7	
Acid exchange and base exchange—blended (cold water)				No advantage over base exchange because HCO ₃ is low											
De-mineralization (cold water)	nil or very small	—	—	—	—	—	—	—	—	4-8	13	nil or very small	—	7	
Distillation (hot or cold)											10			5-6.5	

working conditions the evaporator must be incorporated into the heat balance of the whole boiler plant in the design stage.

The distillate should be nearly as pure as fully de-mineralized water, but it is important to design and operate an evaporator so that carry-over of the concentrated water is avoided at peak loads.

Typical examples of the effects of various methods of softening on the composition of three types of raw water are shown in Table 2.

INTERNAL TREATMENT

This is a combined softening and conditioning treatment carried out in the boiler itself, thus avoiding the installation of a softening plant. The temporary hardness in the raw water is decomposed and precipitated as the water is heated, and the permanent hardness is precipitated in the boiler by the addition of alkali in the form of sodium carbonate, caustic soda, or sodium phosphates. The latter are the most effective precipitants, but because of their cost they are not generally used in the substantial amounts needed when the hardness of the feedwater is high, but for treating feed water for boilers working at pressures above 200 lb./sq. in. or low hardness feedwaters, especially naturally soft upland waters, they are essential.

Organic materials such as tannins, starches, lignins and alginates are often used in conjunction with the inorganic precipitants with the object of forming a more mobile sludge and reducing deposits on heating surfaces. Sodium aluminate is also used for the same purpose. Sodium hexametaphosphate or mixtures of this substance with tannin help to keep economisers and pre-heaters cleaner by delaying the precipitation of CaCO_3 from the raw water passing through them.

The main features of the process are:

- (1) Continuous addition of hexametaphosphate or mixtures of hexametaphosphate and tannin to delay precipitation of hardness in economisers, etc.
- (2) The intermittent addition of precipitating alkalis, alone or mixed with organic materials, to the boiler itself by means of a pump or pressure pot.
- (3) A carefully operated programme of continuous and/or intermittent blowdown to keep the dissolved solids content of the boiler water at a specified concentration and prevent undue accumulation of suspended solids.
- (4) Chemical control of the process by regular tests on samples of boiler and feed water

This treatment has been applied with great success to many boiler plants, having both shell and water-tube boilers. It is usually restricted to waters having a hardness less than 150 p.p.m. CaCO_3 , but has been applied to harder waters under favourable circumstances. The points of chemical addition and the precise chemicals or mixtures to be used must be chosen to suit the water and the boiler operating conditions and the process should not be applied without the guidance of an expert.

BOILER FEEDWATER CONDITIONING

There is usually some residual hardness in a softened water, and small amounts of Ca and Mg salts are often found in condensate due to contamination in the process from which the condensate is derived, or to cooling water leakage in the turbine condenser. In many cases, therefore, small amounts of chemicals are added to the boiler feedwater to counteract scale formation by the residual hardness, and also to adjust the composition of the feed and boiler water to prevent corrosion and caustic cracking. This process of adjustment, is generally known as *conditioning*.

The principles of conditioning against hard sulphate scale formation were worked out by Dr. R. E. Hall in America, following on his studies of the mechanism of calcium sulphate scale deposition. Hall found that by the addition of the right amount of sodium carbonate (Na_2CO_3) to a boiler water containing calcium and sulphate the calcium could be preferentially precipitated as calcium carbonate, which is only slightly soluble in water at boiler temperatures and forms a loose soft sludge or very thin soft scale.

Sodium carbonate decomposes in the boiler, to a degree depending on the working pressure and steaming rate, forming caustic soda (NaOH) which will precipitate residual hardness due to magnesium salts as a sludge of magnesium hydroxide ($\text{Mg}(\text{OH})_2$). It is not practicable to give a definite figure for the amount of Na_2CO_3 to be added in any specific case because it depends on the boiler operating conditions and the amount of sodium carbonate or bicarbonate in the softened feed water; for example, the amount of sodium carbonate left in a water softened by the lime-soda/sodium-aluminate process is often sufficient to prevent sulphate scaling in boilers working at pressures up to 200 lb./sq. in. The proof of correct conditioning in this respect is that the water in the boiler shall have a hardness of less than 10 p.p.m. CaCO_3 when tested by the well-known Wanklyn foam test (see B.S. 1427), or less than 5 p.p.m. by the E.D.T.A. (Versenate) Test, and if this is found not to be the case, then small amounts of sodium carbonate should be added until the boiler water shows zero hardness. The method of addition suggested is as described below for sodium phosphate.

At working pressures above 200 to 250 lb./sq. in. the decomposition of Na_2CO_3 is usually too great to maintain the required concentration of carbonate in the boiler water, and sodium phosphate (Na_3PO_4) is used instead, since the phosphate ion (PO_4) is stable at all boiler temperatures, and calcium phosphate is less soluble than CaCO_3 it also forms as a sludge. The quantity of phosphate added should exceed the equivalent of the calcium in the feedwater by a small amount so as to build up and maintain an excess of Na_3PO_4 in the boiler water amounting to 75–150 p.p.m. to act as a temporary reserve against any unexpected intrusion of calcium salts. To avoid the deposition of calcium phosphate in economisers and preheaters it is customary to add the phosphate *intermittently* at the suction of the boiler feed pump, or to inject it directly into the boiler drum by means of a force pump or displacement vessel. This latter method is preferred when several boilers have a common feed line as it ensures that each boiler receives its proper dose.

Conditioning with phosphate is recommended for all boilers working at pressures above 200–250 lb./sq. in., and in those at lower pressures if the silica content of the feedwater is high, for example, above 10 p.p.m. since it also prevents scales due to calcium and magnesium silicates. Other phosphates such as disodium hydrogen phosphate (Na_2HPO_4) and sodium hexameta-phosphate (NaPO_3)—glassy metaphosphate—can be used when there is surplus of alkali in the softened feedwater.

It is quite common practice to mix organic materials such as starches or tannins with the sodium carbonate or phosphates used for conditioning, to prevent the adherence of the precipitates to the heating and other metal surfaces.

OIL IN FEEDWATER

Oil in feedwater may occur either in suspension or emulsified. Its evil effects are well known; emulsified oil is believed to increase the risk of carry-over or priming, while oil in suspension tends to adhere to heating surfaces and, because of its high resistance to heat transfer, results in overheating of the metal, distortion and possibly rupture.

The source of oil in feedwater is usually condensate from steam passing through the lubricated cylinders of engines. Exhaust from feed pumps is a very likely cause and in this case it is generally better to recover the heat by means of a coil in the feed tank and reject the condensate rather than to attempt to remove the oil from it.

Steam which has been used in back-pressure engines can be partly freed from oil by means of oil separators situated before the process plant, but the lower boiling fractions cannot be removed by this means and must therefore be separated from the condensate. There are several ways in which this can be done, with varying degrees of success. Mechanical methods include tanks in which the oil is removed by flotation. The method is suitable only for water containing a considerable quantity of oil. Filtration through wood wool or sand, or even Turkish towelling, will remove much of the suspended oil, but these methods will not remove emulsified oil where the particles are too small to be filtered off and carry an electrical charge causing them to repel each other. Electrical methods can neutralise the charge and allow condensation of the particles into droplets of sufficient size for mechanical separation.

Chemical means include flocculation with a coagulant such as aluminium sulphate in alkaline solution and subsequent filtration.

Oil can be removed during lime-soda/sodium-aluminate softening, but the method is not recommended except for comparatively small proportions of condensate containing traces of oil.

CORROSION

At boiler temperatures water reacts with steel, to form magnetite (Fe_3O_4) with the evolution of hydrogen, but in boilers it seems that the reaction is quickly brought to a stop because the magnetite forms an adherent layer on the metal surface. Dissolved oxygen would tend to break down this layer and promote fresh corrosion, but caustic soda and sodium phosphate should assist repair at points of breakdown.

Dissolved oxygen can also cause corrosion in economisers and pre-heaters so that the removal of oxygen from the feedwater by vacuum or high temperature de-aeration is the most important counter-measure to corrosion in all parts of the boiler. Experience shows that it is not essential to de-aerate the feedwater to boilers working at pressures up to 250 lb./sq. in., and if the total alkalinity of the boiler water is kept at about 15–20 per cent. of the total dissolved solids content, corrosion in the boiler itself is usually not serious. About one-third to one-half of this alkalinity should be present as NaOH. To limit corrosion of feed lines and other boiler equipment by aerated water, the feedwater should contain sufficient alkali to raise its pH* value to about 9.0.

Above 250 lb./sq. in., the safest course is to reduce the oxygen to not more than 0.05 ml/litre (0.07 p.p.m.) by physical means, and to remove the rest chemically by the continuous addition of sodium sulphite (Na_2SO_3) to the feedwater at a rate which will maintain a concentration of about 30 p.p.m. Na_2SO_3 in the boiler water at all times, the pH value of the feedwater being kept at 9.0 by the addition of caustic soda at the same time if required.

Corrosion caused by carbon dioxide in steam, which makes condensate acid, has already been mentioned (see page 371). Oxygen may be expected to stimulate this attack and may localise it so that deep pits are formed. The best line of approach to this problem is to de-oxygenate the feed and to reduce the bicarbonates in the feedwater to a minimum by a suitable choice of softening process.

Even though the feedwater is fully de-aerated, it appears that corrosion can occur in boilers under piles of sludge lying on or sticking to heating surfaces,

* For an explanation of pH value, see B.S. 1647, and text books.

if its regular removal by blowing down is neglected. The corrosion is ascribed to the destruction of the magnetite layer by high concentrations of caustic soda produced by the evaporation of boiler water trapped under the deposit. This kind of attack has usually occurred in high-pressure boilers, and emphasises the need for careful control of feedwater treatment to minimize sludge accumulation in the boiler.

IDLE BOILERS

Unless special precautions are taken some corrosion is almost inevitable when a boiler is drained and allowed to stand, because some tubes or headers cannot be completely emptied, and the walls of empty drums and tubes are wet. If a period of several months standing is expected, the boiler should be thoroughly dried out with a stream of hot air and then closed up; trays of quicklime being placed in the drums to keep the atmosphere dry. On the other hand if the boiler is to stand for only a week or two, and may be required at short notice, it can be filled up to the top of the drum with alkaline feed-water to which sodium sulphite has been added at the rate of 200–300 p.p.m., samples being tested for sulphite once per week and substantial losses made good. When the boiler is required, all that is necessary is to lower the water to normal working level and blow down a little more heavily during the first few days' working. Superheaters also can become corroded during idle periods and, where they can be completely drained, it will be advisable to fill them with the same solution as the boiler for short standing periods, and to wash out, drain and dry for long standing periods.

CAUSTIC CRACKING OR CAUSTIC EMBRITTLEMENT

This by no means common form of inter-granular cracking brought about by high caustic soda alkalinity and metal strain has been reported both in America and in Britain where research work has not yet succeeded in finding a universal remedy. It is dangerous because it occurs in the crevices between the overlapping plates of riveted seams in the boiler drum, or in the spaces between rivet shanks and heads and the plate, and, therefore, cannot be seen during any ordinary inspection. Furthermore, the first indication of anything amiss may be that rivet heads break off in service or after a light blow with a hammer. Further examination may show the presence of cracks in rivet holes, and, if the plates are taken apart, cracks may be found running from rivet hole to rivet hole on the dry side of the plate, weakening it to such an extent that in some cases explosions have occurred. The cracks are distinctive in that they are usually fine, with many branches, and they pass round the grain boundaries instead of across as in most other types of cracking, so that there is not as a rule much difficulty in identifying them under the microscope. There are almost always signs of leakage in a seam attacked in this way, and a boiler with a history of persistent leakage at riveted seams should be examined by a competent expert.

Experimental work has shown that this type of cracking is produced by NaOH at concentrations above about 7.5 gm/litre (525 gr./gal.) in contact with steel which is under high live tensional stress, such as may be expected around rivet holes, and that the caustic soda in boiler water can concentrate to the required degree as a result of slow leakage to atmosphere between the plates of riveted seams. One obvious remedy is to have all seams caulked on the inside and outside, or to use forged or welded and stress-relieved drums, but there has also been a search for an inhibitor which could be added to the boiler water.

The work of Professor Straub and others at the University of Illinois (1926–30) led to the conclusion that attack by caustic soda could be stopped

if the boiler water contained sufficient sodium sulphate, and the addition of this substance was widely recommended and adopted in the U.S.A. and Britain. The operating experience of the last twenty years shows that caustic cracking is a relatively infrequent occurrence, irrespective of whether sodium sulphate is present in the correct amount. When attack has occurred, however, it is found more often than not that the boiler waters are low in sulphate, but in a small number of stationary boilers the attack has occurred, apparently despite the presence of adequate amounts of sodium sulphate. It seems reasonable to conclude that the use of sodium sulphate in stationary boilers has made them less liable to attack, but that the remedy sometimes fails. Experience on certain American railways shows that there is a considerable amount of evidence that in their type of mobile boiler sodium sulphate is ineffective.

There has therefore been a search for other inhibitors and there are now three chemical methods that can be considered for treating boiler water to prevent caustic attack, viz:

(a) The "Co-ordinated phosphate treatment"

This was first proposed and used by Purcell and Whirl in America and is sometimes referred to as the "zero-caustic" or "captive alkalinity" method.

The treatment consists in the addition of acid phosphates to the boiler water in order to destroy free caustic soda and form trisodium phosphate, together with a little disodium phosphate. After this treatment the hydroxide concentration in the boiler water is negligible so that even if concentrated by evaporation through a leaky seam it does not cause caustic attack.

The treatment is more expensive than other methods, especially when the caustic soda concentration in the feedwater is high and, possibly for this reason, it has not been used extensively. Nevertheless, it is the logical chemical approach to the problem and should therefore be carefully considered in each case before other methods are adopted. So far there have been no reports of caustic attack in boilers treated in this way.

(b) Sodium nitrate

It is claimed that sodium nitrate has been found to have a pronounced inhibitive effect in American laboratory tests, and it has been officially recommended by the American Railway Engineering Association for use in locomotive boilers where it has proved very successful in reducing the incidence of caustic cracking. It has also been used during the last few years in some stationary boilers with apparent success. So far as is known it has been tried in only a few boiler plants in Britain. It is recommended that NaNO_3 be added until the natural nitrate content of the feedwater is raised to the point at which the ratio: $\text{NaNO}_3/\text{total alkalinity}$ expressed as NaOH , is equal to or greater than 0.4. This recommendation applies only to boilers working in the range 100–500 lb. sq. in. Experience at higher pressures is not yet available. No detailed study of the mechanism of protection by sodium nitrate has yet been published.

(c) Sodium sulphate

The recommendation widely adopted in Britain is that the boiler water shall contain sufficient sodium sulphate to maintain the ratio: sodium sulphate/caustic soda greater than 2.5 at all times. If the natural sulphate content of the feedwater is not high enough, then sodium sulphate must be added.

To assist in choosing the appropriate treatment it is suggested that method (a) be considered first only when the feed-water consists mainly of condensate, and secondly that nitrate or sulphate is chosen depending on cost and the increase in dissolved solids which they bring about. Should any feed-water

contain enough of either to maintain the recommended conditions without addition of chemical, no treatment need be applied.

Sodium nitrate and sodium sulphate are preferably added to the feed-water continuously as solutions and this is specially important when treating groups of boilers, as it ensures that each boiler receives its proper share of chemical. Acid phosphates should be added intermittently—once per shift—direct to the boiler drum, because continuous addition to the feed-water may easily cause precipitation of solid in economisers and feed lines if there is any hardness present in the feedwater.

STEAM PURITY

The purpose of the boiler plant is to make steam that will not cause corrosion or deposits in superheaters, turbines or process plant. Corrosion by carbon dioxide and oxygen in the steam has already been mentioned but the steam can also contain salts as a result of entrainment or carry-over of particles of boiler water.

As the steam passes through the superheater these particles dry out and solid salts may be found at various points in the system, e.g. inlet header boxes and inlet tubes of superheaters, outlet header boxes, in steam lines, on steam valve spindles, turbine governor valves, and turbine blades. The presence of boiler water salts in condensate from steam traps and process plant, or deposits in process plant may also indicate carry-over.

The presence and amount of salts in steam may be determined by means of special sampling nozzles inserted in the steam lines, the sample being cooled and condensed and the dissolved solids determined either by evaporation to dryness in the laboratory or by measurements of conductivity. For boilers working at high output or high pressure, or where especially pure steam is required for process, apparatus of this kind, fitted to each boiler and coupled to de-gasifying towers and continuous conductivity recorders, provides a useful additional check and control on the operation of the boiler. Sudden rises and falls in steam conductivity may indicate a tendency to prime, which can be counteracted by lowering the boiler water level or reducing boiler output, whereas a steady increase in conductivity probably indicates continuous carry-over, which can usually be diminished by blowing down to reduce the concentration of dissolved salts in the boiler water.

Some superheater failures may be explained on the supposition that when the boiler is shut down the salts on the walls will dissolve in the condensate and drain down, to the lowest parts of the superheater, where they will be concentrated by evaporation when the boiler starts up again and destroy the magnetic oxide layer on the metal, thus exposing it to fresh corrosion. Such a set of circumstances is more likely to occur in superheaters that cannot be completely drained, and it is suggested that it might be a useful precaution to wash out the superheater with condensate whenever salt deposits are observed at the inlet ends.

Experience shows that carry-over of boiler water is usually promoted by circumstances such as high water levels, sudden changes in steam load, leakage past baffles in the steam drums, and the concentration of suspended and dissolved solids in the boiler water, or the presence of oil, operating together or independently. The influence of the dissolved solids in boiler water has been widely studied, and it seems to be established that for any given set of steady boiler operating conditions the entrainment of particles of boiler water increases rapidly when the concentration of dissolved solids in the boiler water exceeds certain figures. Table 3 gives a rough indication of these critical concentrations in boilers working under steady load and at the maximum continuous rating (M.C.R.) specified by the boiler manufacturer.

TABLE 3
MAXIMUM PERMISSIBLE T.D.S. IN BOILER WATERS

Type of boiler	p.p.m. (approximate figures)*			
Economic boilers	4,500
Lancs.	17,000
Loco.	3,500
Vertical	4,500
				(may be 3,000 on highly rated boilers)
Water-tube boilers				
0-200 lb./sq. in.	15,000-10,000
200-300 lb./sq. in.	10,000-5,000
300-600 lb./sq. in.	5,000-2,500
600-900 lb./sq. in.	2,500-1,500
Above 900 lb./sq. in.	1,000

*Assuming the water to be reasonably clear, i.e. free from cloudiness or suspended matter.

To prevent the concentration from rising above these figures boiler water is blown to waste. This represents a loss of fuel and degradation of energy, only partly compensated for by a heat recovery system. Blowdown must, therefore, be restricted to the barest minimum needed to maintain the recommended conditions.

The figures in Table 3 and the T.D.S. column of Table 2 can be used as an indication of the amount of blowdown to be expected by the use of a given water after treatment by a particular softening process. For example, the surface water shown in Table 2 after treatment by hot lime-soda/sodium-aluminate will have a T.D.S. of about 300 p.p.m. and if used as 100 per cent., make-up to a boiler working at say 180 lb./sq. in. could be allowed to concentrate to about 15,000 p.p.m., according to Table 3. The blowdown required would, therefore, be $\frac{300 \times 100}{15,000} = 2$ per cent., but at 900 lb./sq. in. the blowdown

would be $\frac{300 \times 100}{1,200} = 25$ per cent., so that at least 50 per cent. of condensate would be required to make the final feed-water acceptable, unless some other method of treatment such as de-mineralisation were applied, or a purer water supply made available. Figures corresponding to those shown in Table 2 can be worked out for any water supply and the choice of water supply and method of treatment fitted to the needs of the boiler plant, or the maximum boiler pressure chosen to fit the water supply. The choice of boiler working pressure usually depends on a number of requirements, but to avoid unexpected difficulty or expense in water treatment it is advisable to make some simple calculations of this type at the design stage of the boiler plant.

ANTI-FOAMS

There are now available mixtures of chemicals which when added to a boiler water prevent the contamination of steam at much higher concentrations of boiler water salts than the figures shown in Table 3. For example, it has been shown that some locomotive boiler waters can be allowed to concentrate to as much as 30,000 p.p.m. before carry-over begins. It is believed that the chemicals act by suppressing the formation of a layer of foam on the top of the boiler water, and wherever steam contamination is troublesome the use of antifoams should be considered.

DISPOSAL OF BLOWDOWN

There are four methods of disposing of blowdown, viz. :

- (1) Blowing to waste: *If this method is adopted the most rigid control is necessary to prevent waste of fuel.*
- (2) Passing through a heat exchanger, in which the feedwater is heated, or through a flash vessel from which the steam is passed direct into the feedwater and the heat in the residue is recovered in a heat exchanger. Alternatively, part of the residue from the flash vessel can be returned to a hot softening plant in which its heat and chemical content are used.
- (3) Returning a portion of the blowdown direct to the feed so that the chemicals in it are used for conditioning purposes. As a rule the amount of blowdown recoverable in this way is small.
- (4) Using the blowdown from high pressure boilers working on good quality feedwater as feedwater make up to low pressure boilers. For example, in one case the blowdown from 650 lb./sq. in. boilers is used as part feed to boilers working at 200 lb./sq. in.

Continuous blowdown is the most satisfactory method of removing water from the boiler because it can be easily adjusted to maintain the T.D.S. in the boiler water consistently at the desired level. The method preferred in water-tube boilers is to fit a short horizontal length of pipe below the water level in the steam-water drum and at the end opposite the feed entry. In cylindrical boilers an open-ended vertical pipe may be used, but the open end should be more than two inches above the top of the main flue tubes so that these cannot be exposed through excessive blowdown. An orifice of suitable size or a fine control valve is fitted in the blowdown line outside the boiler to control the amount discharged, and should be adjusted to maintain the desired T.D.S. in the boiler water. Continuous blowdown is not recommended when the amount of water to be removed is less than 25 gallons per hour.

Most boiler waters contain some sludge which must be removed by intermittent operation of the ordinary bottom blowdown valve. This valve should be opened as often as is reasonable, taking into account the total volume of water to be removed, i.e. once per shift, or not less than once per day, so that the concentration of salts in the boiler water is kept fairly steady.

To ensure removal of accumulated sludge the valve should be opened momentarily several times with a short pause in between so that the disturbance in the neighbourhood of the valve can die down and fresh sludge move into position ready to be flushed out.

When feedwaters of low T.D.S. are used, or the rate of evaporation is low, and the maximum permissible T.D.S. in the boiler water is high, it may be found that this figure is reached only after several weeks running, and perhaps not at all. In such cases the intermittent blowdown should be operated once per day after the first few days working.

It is advisable to have a clear set of blowdown instructions issued to each boiler-house covering all conditions of operation.

SILICA IN STEAM

There have been several papers in the American and German technical press reporting the occurrence of gross deposits of silica on the blades of condensing turbines at the low pressure end, and experimental work carried out by Professor F. G. Straub, of the University of Illinois, has shown that at boiler pressures above 1,000 lb./sq. in. silica in boiler water can dissolve in the steam, probably in the form of silicic acid, and crystallise out on the turbine blades as the steam temperature drops. Most of the worst cases of silica deposits reported from America have been in boiler plants working at 1,200 lb./sq. in.

or above. It has been found that the deposits can be prevented if the silica content of the boiler water is kept below about 50 p.p.m. in boilers working at 1,000 lb./sq. in. and below 5 p.p.m. at 1,600 lb./sq. in. or higher pressures. In some cases this limitation involves special treatment to remove silica from the feed water. So far there seem to have been no comparable experiences in Britain, but the problem must be kept in mind when higher boiler pressures are contemplated.

HOT WATER HEATING SYSTEMS

Water heating systems used for space heating are practically always closed circuits requiring little or no make-up water. Difficulties due to scale and corrosion are, therefore, comparatively rare but the following general observations may be of interest:

- (i) Make-up should be reduced to an absolute minimum. Deliberate draw-off should be eliminated and accidental losses avoided as much as possible.
- (ii) With certain arrangements of mechanical stoker very local intense heat is produced in sectional boilers, with the result that scale-forming matter is deposited on a small area of metal. The black sludgy material which commonly forms in these circuits becomes incorporated and increases the volume of the deposit. The only practical answer is to avoid this type of localised heat.
- (iii) As far as possible the circuit should be fabricated in one metal. Troubles with ferrous and cuprous metals in conjunction are confined to a few types of water but ferrous metals are sufficiently durable in most closed circuits to justify their sole use.

A special type of hot water system is one in which a steam boiler is used to provide hot water for circulation. The advantage of such "pressure hot water heating" systems is that the benefit of high temperature is available without the disadvantages of steam trapping and condensate return. If little make-up is used scale formation will not be appreciable but as the results of corrosion in the circulation system might be very serious it is usually advisable to treat such systems as ordinary steam-raising plant, water conditioning including sodium sulphite treatment to remove dissolved oxygen. When a boiler serves a dual purpose for steam raising and hot water heating, soft water make-up is essential to avoid appreciable amounts of sludge in the circulation.

HOT WATER SUPPLY SYSTEMS

The two water treatment problems in hot water supply systems are calcium carbonate scale formation and corrosion. Scales due to calcium sulphate or silicate or to magnesium compounds are uncommon. Corrosion may be fairly uniformly spread over the metal surfaces or may take the form of pitting, and the products of corrosion may be deposited on site or carried forward to other parts of the system, where they may choke pipes.

Calcium carbonate scales are caused by the decomposition of calcium bicarbonate, with the evolution of carbon dioxide. Methods available for control are (i) temperature limitation, (ii) softening and (iii) addition of inhibitors. Some control may also be obtained by reducing the flow of water at the outlet valve so that the system is maintained under slight pressure. Rise in temperature increases the scale formed so that any temperature control that can be imposed will reduce the scale problem. It is, however, rarely satisfactory to rely solely on thermostatic control applied to the hot water discharging from a direct-heater used with hard water. This is because of the high local "skin" temperatures that occur. An approach which is often satisfactory is to use an "indirect system" in which there is a primary closed circuit to transmit

the heat from the heater (solid fuel, gas or electric) to the hot water supply in a secondary circuit. Such systems require much more space than direct systems. Steam-heated calorifiers are less troublesome than "direct" systems, especially at low pressure, but the "separate" type in which the water space is small is not suitable for hard water. It may be found desirable on occasion to by-pass a small proportion of hard water and blend it with the *zero soft* supply from the softener.

Softening is probably the most satisfactory method of dealing with hard waters for hot water supply, particularly for domestic use or for certain process purposes. Either precipitation or zeolite processes may be used, but if plant is being installed for hot water only, the more convenient, and usually cheaper, zeolite plant may be preferred.

Where scale-prevention is required but softening is not possible, threshold treatment with glassy metaphosphates can be used. Applied at the rate of a few parts per million, these compounds interfere with the crystallization of calcium carbonate and so induce an apparent super-saturation. Above 180° F. the glassy metaphosphates are converted into orthophosphates which do not possess the same property but if the contact period at high temperature is small a considerable reduction in scaling may be expected.

Corrosion in hot water supply systems can usually be avoided by suitable choice of materials but even with the more resistant materials difficulties are occasionally experienced. Soft waters with pH values under 7.0 (acidic waters) are particularly troublesome with non-ferrous metals. With lead they may pick up sufficient metal to make them dangerously toxic; with copper sufficient metal may go into solution to produce green stains on fittings or fabrics or even to discolour the water. In such cases raising the pH value with an alkali such as caustic soda, hydrated lime or silicate of soda is usually a satisfactory treatment. Over-dosing must, however, be avoided.

Both soft and hard waters may be corrosive to ferrous metals, though more difficulty is experienced with the former. Lime softening of corrosive hard waters is often effective; the added lime removes dissolved carbon dioxide as well as hardness. Zeolite-softened waters are usually blended with a small proportion of hard water to reduce this corrosiveness and also to economise in salting costs. In some instances the addition of an alkali is also necessary, however. Alkali additions to corrosive hard waters are also often effective but simultaneous addition of an inhibitor is usually required to prevent scale deposition which will otherwise be increased by the alkali addition.

Chemical conditioning of corrosive soft waters for use in ferrous metal systems is more difficult as addition of alkali alters the nature of the corrosion products. Below a pH value of 7.0 corrosion tends to be general and corrosion products are carried away with the water, but in the range of approximately 7.5-9.0 the corrosion products adhere to the metal in the form of "tuberculation" and corrosion is more localized. If it is possible to raise the pH value to over 9.0 corrosion control is often successful, and sodium silicate is sometimes effective. Some inhibitors which would otherwise be effective, such as the chromates and various metallic salts, are toxic and cannot be used for domestic or many trade purposes. When the rate of flow is sufficient to ensure a continuous supply of inhibitor to the metal surface the glassy metaphosphates can be used, although the amount required is more than for scale prevention and no protection is afforded to tanks or other large surfaces where lack of turbulence prevents the necessary supply of inhibitor from reaching the metal surface. For tanks, certain proprietary protective coatings, or sprayed aluminium for hot tanks and cement-wash or bitumen for cold tanks can be used.

GENERAL PRINCIPLES

The general principles of boiler feedwater treatment are summarized below, but it must be emphasized that not all the qualities mentioned are essential in any given case and expert advice should be sought when choosing a treatment, a point that cannot be too strongly emphasised.

(1) Choice of softening process to yield final feedwater having:

- (a) Low total dissolved solids—to reduce boiler blowdown.
- (b) Low hardness—to avoid sludge in the boiler.
- (c) Low bicarbonate—to prevent corrosion by steam.
- (d) Low alumina and low silica where necessary.

(2) Conditioning treatment:

- (a) Sodium carbonate to prevent scaling in boilers working at pressures below 200 lb./sq. in. Hardness in boiler water should be nil. (See p. 380.) Some methods of water softening leave sufficient sodium carbonate in the treated water.

- (b) Phosphates—for scale prevention in boilers at pressures above 200 lb./sq. in. or in low pressure boilers if the silica content of the feedwater is much above 10 p.p.m. Phosphate reserve in boiler water 75–100 p.p.m. Na_3PO_4 .

- (c) To prevent corrosion in feed lines, and in boilers working at pressures up to 250 lb./sq. in. the feedwater should be alkaline to phenolphthalein and the total alkalinity of the boiler water should be 15–20 per cent. of its total dissolved solids content. About one-half of this alkalinity will usually be present as NaOH. Some softened waters contain this amount of alkali.

At 250 lb./sq. in. to 900 lb./sq. in. it is suggested that the feedwater should have a pH value of 9.0, and the boiler water a caustic alkalinity of 5 to 10 per cent. of the T.D.S. content. The feed-water must be de-aerated to reduce oxygen to less than 0.05 ml./litre, and it is advisable to supplement this with chemical de-aeration using sodium sulphite in sufficient amount to maintain an excess of sulphite in the boiler water at 35–70 p.p.m. Na_2SO_3 .

- (d) Addition of chemicals to guard against caustic embrittlement in boilers fitted with riveted drums. (See pages 382–3.)

- (e) Internal treatment for shell and low pressure water-tube boilers if the water supply has a hardness of less than 150 p.p.m. CaCO_3 , and bicarbonate is not too high.

(3) Blowdown Control

Control of blowdown to maintain the T.D.S. content of the boiler water in the ranges given in Table 3. Intermittent blowdown to reduce the amount of sludge in the boiler to the lowest possible amount, without excessive loss of heat.

(4) Testing

The institution of a schedule of regular testing to observe and control the treatment at all stages.

(5) Idle Boilers

Special addition of sodium sulphite to protect idle boilers against corrosion.

CONTROL OF WATER TREATMENT

To secure satisfactory softening and conditioning requires control by routine testing. Most of the methods of test are simple and rapid, and it is of course important that immediate action should be taken on the results to modify the softening or conditioning chemical charges as required. Testing should be carried out in a clean and well-lighted place, shut off from boilerhouse fumes and dust, and supplied with hot water for cleaning the glassware used.

It is impossible to specify in detail the tests which should be made for every plant owing to the differences in operating conditions, and expert advice should be sought, but a summary of tests usually required is given below.

Instructions for sampling and testing are given in B.S.S. 1328, "Methods of Sampling Water Used in Steam Generation" and 1427 "Tests for Water Used in Steam Generation".

Water Softening—Lime-soda Process

Raw water

Waters from rivers and canals usually vary in composition with the season of the year or after heavy rainfall. Daily average samples usually suffice for softening plant control purposes, and if these show that the composition of the water is reasonably constant the control of the plant may be based on tests on the softened water only. If these fail to give the desired results, the raw water should be tested again. It is advisable to take samples of the raw water at all times of the year and after heavy rainfall so as to build up a history of its probable changes in composition.

Data required (filtered sample)

Total alkalinity to methyl orange (temporary hardness).

Hardness due to lime salts

Hardness due to magnesia salts

} The total hardness is the sum of these,

all expressed as p.p.m. CaCO_3 .

The total alkalinity of surface waters is usually less than the total hardness and the water is said to have both temporary and permanent hardness, but in some well or spring waters the reverse is the case and these waters contain free sodium bicarbonate, all the hardness being present as temporary hardness. Waters having a total hardness less than about 80 p.p.m. CaCO_3 would be softened by base exchange or treated inside the boiler as described under "Internal Treatment", p. 379. They are, therefore, not considered here.

Water containing free sodium bicarbonate

In this case lime alone is sufficient to precipitate all the hardness. The lime also converts sodium bicarbonate into sodium carbonate, and for boiler feed purposes it may be necessary to destroy or neutralise some of this by adding calcium chloride, calcium sulphate, magnesium sulphate or sulphuric acid, to avoid excessive alkalinity in the boiler water. The amount of these salts added should destroy all but about 50 p.p.m. CaCO_3 of the alkalinity due to sodium carbonate in the lime-softened water.

Commercial calcium chloride contains only 70–72 per cent. of CaCl_2 . Consequently, in order to destroy the alkalinity equivalent to 1 p.p.m. of CaCO_3 it is necessary to use about 1.57 p.p.m. of commercial calcium chloride, according to the equation: $\text{Na}_2\text{CO}_3 + \text{CaCl}_2 = \text{CaCO}_3 + 2\text{NaCl}$.

(m.w.110) (m.w. 100)

the calculation for 70 per cent. CaCl_2 being thus $\frac{110}{70} = 1.57$.

If gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is chosen, 1.75 p.p.m. will be required for every one p.p.m. of CaCO_3 alkalinity due to sodium bicarbonate to be destroyed.

Softened Water

Data required

Total alkalinity to methyl orange
(as p.p.m. CaCO_3)

Caustic alkalinity
(as p.p.m. CaCO_3)

Residual hardness (total)
(as p.p.m. CaCO_3)

} Daily average sample and snap samples once per shift if composition of raw water is reasonably constant. More often if chemical charges are being altered.

Hardness due to lime salts

(as p.p.m. CaCO_3)

Hardness due to magnesia salts

(as p.p.m. CaCO_3)

} Occasionally required as a check

Hardness in suspension

(as p.p.m. CaCO_3)

Daily snap sample to check efficiency of filters, particularly wood wool filters.

Samples of softened and filtered water should be taken from the softening plant outflow pipe after the plant filters and three to four hours after any changes in chemical doses are made. The sample should be filtered through filter paper and tested *immediately* because caustic alkalinity is converted to carbonate when the sample is exposed to air. A figure for suspended hardness is obtained from the difference between total alkalinity determinations done before and after filtering through filter paper. The residual hardness should be of the order of 15 to 30 p.p.m. CaCO_3 when softening is carried out at atmospheric temperature but about 10 p.p.m. CaCO_3 or less if the softening temperature is above 70°C . The hardness is due to the slight solubility of calcium carbonate and magnesium hydroxide; since these two substances also react with the acid used in the determination of total alkalinity, this figure represents residual hardness *plus* excess chemicals (Na_2CO_3 and NaOH).

The conditions to be fulfilled in a properly softened water are:

- (1) Total alkalinity should exceed residual hardness by about 80 p.p.m. CaCO_3 .
- (2) Caustic alkalinity should exceed residual magnesia hardness by about 30 p.p.m. CaCO_3 .
- (3) Carbonate alkalinity should exceed residual lime hardness by about 50 p.p.m. CaCO_3 .

If the softened water does not comply with rule 1, then the amounts of chemicals must be increased until it does. Rules 2 and 3 require determinations of lime and magnesia. As this takes time, a rough check may be made by assuming that the residual hardness due to magnesia is about one-half to one-third of the total residual hardness. The newer test for hardness, using E.D.T.A. or "Versenate", enables calcium hardness to be readily determined, and magnesium hardness can be obtained by difference.

The rules for changing caustic and carbonate alkalinities are:

- (1) To increase carbonate alkalinity only, add sodium carbonate, and *vice versa*.
- (2) To increase caustic alkalinity only, add hydrated lime and sodium carbonate.
Note: each unit weight of hydrated lime requires $1\frac{1}{2}$ units weight of sodium carbonate for this purpose.
- (3) To increase carbonate alkalinity and decrease caustic alkalinity at the same time, reduce the amount of hydrated lime, and *vice versa*.
- (4) For these adjustments, alterations of 5 to 10 per cent. by weight of each chemical are convenient steps.

Water Softening—Base Exchange

Zeolite softening plants are usually operated on a volume basis, i.e. the units are regenerated automatically or by hand after a definite volume of water has passed through. This volume is calculated from the known hardness-removal capacity of the bed of exchange material (information given by the plant suppliers) and the amount of hardness in the raw water.

Determinations of total hardness of the raw water should therefore be made once a day so that, if there is a marked increase, the volume of water passing through each exchange unit can be decreased in proportion, and *vice versa*. To make certain that each unit is softening properly the total hardness of the softened water can be determined two or three times during the last hour before any unit is expected to be exhausted. This is really necessary only when the raw water changes frequently and rapidly or the softened water is used for purposes requiring water of constant composition, e.g. boiler feed, particularly in the medium and high pressure ranges, and soap-using processes. If the water is used for boiler feed, the total alkalinity should also be determined on the softened water, so as to be forewarned of changes in the alkalinity of the boiler water.

If the hardness of the raw water is reasonably constant, or changes only slowly, then a daily drip average sample from each unit together with one check test of hardness just before regeneration should suffice. As soon as the residual hardness in the softened water rises above 5-10 p.p.m., as CaCO_3 , the unit should be regenerated. Hardness recorders are now available.

Boiler Feed Waters

Boiler feed waters may consist of condensate plus evaporated make-up, condensate *plus* treated water make-up, or treated water make-up alone. A feedwater should not cause corrosion or scale in feed lines or economisers and for this purpose it must be alkaline and soft. The pH value should be 9.0-9.5. Mixtures of condensate and lime-soda softened water will usually contain sufficient alkalinity owing to the excess alkali present after the softening.

Scaling in economisers is reduced to a minimum by keeping the hardness of the feed as low as possible and by continuous addition of glassy metaphosphate or mixtures of that substance with tannins.

The usual tests required are, therefore:

Total alkalinity	} These may be done once per shift if the feedwater composition varies, but once per day if it is reasonably steady.
pH value	
Hardness	

Dissolved oxygen. To check performance of de-aerators (for high pressure boilers a recorder is advised).

The addition of conditioning chemicals is controlled by tests on the boiler water. The tests and frequency of testing will depend on the boiler operating conditions, the treatment, and the number of boilers. Suggestions for sampling are given in B.S. 1328. The usual tests required on a boiler and an indication of frequency are as shown in Table 4.

TABLE 4

TESTS FOR CONTROLLING OF ADDITION OF CONDITIONING CHEMICALS

Test	Frequency
Total alkalinity	Daily
Caustic alkalinity	Daily.
Hardness	Daily.
Total dissolved solids	Daily. For blow-down control.
Sulphate or nitrate	Not less than twice weekly on each boiler, but see below
Phosphate (where used) ..	Daily
Sulphite (where used) ..	Daily.

The results of the tests should be calculated as follows :

Caustic alkalinity (To convert p.p.m. CaCO_3 to p.p.m. NaOH ,
as NaOH . multiply by 0.8.)

Hardness as CaCO_3 .

Sulphate as Na_2SO_4 .

Nitrate as NaNO_3 .

Phosphate as Na_3PO_4 .

Sulphite as Na_2SO_3 .

Sulphate/caustic ratio as $\text{Na}_2\text{SO}_4/\text{NaOH}$.

Where boilers are working with the same feed-water to which any conditioning chemicals such as sodium sulphate are added continuously, it is recommended that all boilers of the same type and working pressure should be considered as a Group. Snap samples of boiler water from each boiler of each Group should be tested daily for NaOH and dissolved salts, and the samples from the boiler having the highest NaOH /dissolved-salts ratio and hence the smallest sulphate/caustic ratio should be tested for Na_2SO_4 . If this ratio is low in the selected boiler water then the amount of Na_2SO_4 to be added to all boilers in the Group must be increased.

If sodium sulphate or other conditioning chemicals are added intermittently, and in amounts which may substantially alter the dissolved solids in any boiler, it is better to use the method of sampling recommended in B.S. 1328. In this, similar types of boiler working at the same pressure are divided into groups of three or four, and a daily snap sample is drawn from one boiler in each group, taking the boilers of each group in rotation. This sample is tested for Na_2SO_4 and NaOH , and is used as a marker for the condition of the other boiler waters in the same group.

When sodium nitrate is used instead of sodium sulphate the same methods of sampling may be used. The NaNO_3 in the selected sample can then be determined and the ratio NaNO_3 total alkalinity expressed as NaOH can be calculated.

If the "co-ordinated phosphate" treatment is used then each boiler should be tested for NaOH every day. This can be done by titrating a sample of boiler water containing phenolphthalein and screened methyl orange with 0.1 M acid until the pink colour of the phenolphthalein disappears (=P) and continuing to the methyl orange end-point; the total titration=M. Then

$$M = \text{NaOH} + \text{Na}_2\text{CO}_3 + 2/3 \text{Na}_3\text{PO}_4$$

$$P = \text{NaOH} + \frac{1}{2} \text{Na}_2\text{CO}_3 + 1/3 \text{Na}_3\text{PO}_4$$

and caustic soda is present if 2P is greater than M. More acid phosphate must then be added.

Much remains to be learned about the chemistry of boiler water, but as a result of experience certain characteristics in feed and boiler waters that have given good results can be laid down in general terms as shown in Table 5. The division of boilers into three pressure groups is quite arbitrary. It is not claimed that all boiler plants work to these figures or that deviations from them will be disastrous. They are offered as a reasonable guide, and the principal evidence of the efficiency or failure of boiler water treatment must be the appearance of the internal surfaces of the boiler and its freedom from breakdown due to corrosion or scaling.

TABLE 5
RECOMMENDED WATER QUALITIES FOR BOILERS

FEED WATERS	<i>Low pressure: up to 250 lb./sq. in.</i>	<i>Medium pressure: 250-500 lb./sq. in.</i>	<i>High pressure: 500-1,000 lb./sq. in.</i>
Hardness (p.p.m. CaCO ₃)	Preferably not more than 10	5-10 max.	Less than 5
Total alkalinity ..	As required to give the figures for alkalinity and hardness given in the boiler water section below.		
pH value	9.0	9.0	9.0
BOILER WATERS			
Hardness (p.p.m. CaCO ₃)	Zero by Wanklyn foam test	Less than 5.0 by E.D.T.A. test	
Total alkalinity ..	15-20 per cent. of the total dissolved solids	As arising from the feedwater and addition of phosphate for conditioning pH should be not less than 11.	
Na ₂ SO ₄ /NaOH	Ratio always above 2.5 in boilers with riveted drums*		
Na ₂ PO ₄ (p.p.m.) ..	50-100	50-100	50-100
Na ₂ SO ₄ (p.p.m.) ..	—	20-30	20-30
Total dissolved solids (p.p.m.)	15,000 to 5,000 at high pressure end of range	5,000-2,500	2,500-1,000
See also Table 3 page 385			

*See page 383.

BOILER WATER MANAGEMENT

Whatever methods of treatment are used it should be recognised that the changes that take place in water during preliminary treatment, and in the boiler under the influence of heat and evaporation, are chemical changes which must be controlled at all stages in the process of converting water into steam. It is suggested, therefore, that where the boiler plant is large, or working at high pressure, full responsibility for the supervision and direction of water treatment should be given to a chemist, who should have sufficient knowledge of modern water treatment practice, and of the design and operation of boilers, to advise the engineer in charge on the treatment and control tests required, and to explain the reasons for them. In many large works there is scope for such a man in the study and solution of other water treatment problems, such as the prevention of scale, bacteriological growths and corrosion in cooling systems and condensers, or the treatment and disposal of works effluents. In view of recent legislation, the latter will require much more attention than it has hitherto received.

When a chemist is not available, a consultant can help materially by paying periodical visits, making check tests, and teaching the boiler staff to carry out simple control tests and the action to be taken in the light of the results. Many small boiler plants are successfully controlled in this way after preliminary consultation with an expert. The correctness and efficiency of any form of feed water treatment can be gauged only by frequent and regular tests done by a competent tester whose results are confirmed at regular intervals by a qualified analyst specialising in this work.

COOLING WATER CIRCUITS

Water used for cooling in industrial plants is used either once only or continuously in circulating systems provided with cooling towers. The

cooling water after use in a once-through system may be used for other industrial purposes and any treatment given to it will have to take this into account.

Once-through systems are often trouble-free but if temperatures are high and the water contains an appreciable bicarbonate hardness, softening or the use of glassy metaphosphate inhibitors may be required. With corrosive waters, resistant non-ferrous metals such as copper, copper-nickel or aluminium brass are generally employed but where ferrous metals are in use corrosion inhibitors must be added. Chlorination (first used at Hackney Power Station, London), for control of bacterial slimes may also be required.

Circulating systems lose water by evaporation and also by mechanical carry-over, the relative amounts depending on the temperature differences in the circuit and the design of cooling tower. Under constant conditions the concentration of dissolved solids will rise to a limit which is given by the following expression:

$$\begin{aligned} \text{Concentration Factor} &= \frac{\text{Dissolved solids in circulating water}}{\text{Dissolved solids in make-up water}} \\ &= \frac{\text{Water lost as liquid and vapour}}{\text{Water lost as liquid}} \end{aligned}$$

The liquid losses include not only mechanical carry-over but accidental leakages and deliberate bleed-off or purge. The concentration factor is measured by comparing the concentration of an ion which during concentration is neither removed from the system nor added to it; the chloride ion is often suitable, but if the system is subject to chlorine additions the magnesium concentration is sometimes used. It is of value in estimating the amount of any reagent required in the make-up water to maintain a given concentration in the circulating water. It can also be of use in controlling purge or bleed-off where this is used or in conjunction with other determinations in detecting entry into a system or losses from it as, for example, by scale formation.

Calcium carbonate is the chief scale former but calcium sulphate also forms scale because its solubility decreases with rising temperature. If the solubility of calcium sulphate (2,000 p.p.m. at 40° C.) is likely to be exceeded it can be removed by softening, the temperature can be lowered, or the concentration can be reduced by increased bleed-off.

Calcium carbonate is often converted by means of nitric acid to calcium nitrate, which is innocuous in such systems, but the acid-dosing requires meticulous care. Carbon dioxide liberated by acidification is lost in the tower or spray jets so that a good place to add the acid is before these units. Threshold treatment with glassy metaphosphate can be applied, when it is practicable, to control the concentration factor so that the calcium bicarbonate concentration (as CaCO_3) multiplied by the concentration factor does not exceed 300–350 p.p.m.

In cooling systems bacterial slimes can be controlled by intermittent chlorination applied by means of a gas-chlorinator in large systems or as sodium hypochlorite solution in small systems. The treatment is often also effective in preventing the green algal growths which flourish in cooling towers.

Copper sulphate which is used in reservoirs for control of green algae is not usually advisable in industrial cooling circuits owing to the possibility of bi-metallic corrosion cells being set up following deposition from copper salt solutions on ferrous metals.

Among the more recently introduced compounds for control of organic slimes is sodium pentachlorophenate. It may prove to have advantages in small systems but its use in Britain is still in its infancy. This is a poison and its adventitious access to other waters must be carefully guarded against.

Corrosion in circulating systems can frequently be restrained by controlled precipitation of calcium carbonate on the metal with or without glassy metaphosphate inhibitors. For soft water the last by themselves may sometimes be used. Other inhibitors include the chromates, sodium benzoate, sodium nitrite, sodium silicate and certain organic compounds such as NaMBT (sodium mercaptobenzothiazole). The selection of inhibitors must, however, be undertaken in collaboration with a specialist and must take into account the nature of the system, particularly the metals used in its construction. It is also necessary to avoid damage to surrounding property by windage distribution or excessive quantities of toxic chemicals in "bleed-off" finding their way to surface streams or to small sewage plants.

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CHAPTER 17

THE PROPERTIES AND USES OF STEAM

This Chapter treats this very big subject very briefly. For fuller information on steam and its uses, the reader is referred to the companion volume "The Efficient Use Of Steam," published by H.M. Stationery Office¹; References to that book are made in this Chapter after the initials "E.U.S."

MOST of the coal mined in Britain is used for heating water. For some purposes, such as central heating, textile processing, etc., the hot water is used directly, but for most purposes the water is converted into steam, which is used to generate power by means of steam engines or turbines or to supply heat for various processes. As all the heat in the steam from the exhaust of engines and turbines is wasted, the best way of making the utmost use of the heat is to use the steam for generating power and then use the exhaust steam for process heating. The amount of fuel used to generate power, even in a small factory, is thus reduced to less than half of what is required by the best condensing power station.

It is a common boast of a factory manager or engineer that he keeps a tight control of the factory's boiler efficiency; each extra one per cent. of efficiency gained is looked on as a triumph. Very different is the attitude generally adopted towards the *use* made of the steam once it has left the boiler house; it is quite common to find factories using twice as much steam as is really needed.

In most factories the responsibility for controlling the use of steam must almost necessarily be carried by someone other than the one who has produced it in the boiler house. As the user may not have had any training in steam technology, waste of steam is almost sure to occur. All those who have charge of steam-using plant should learn the elementary properties of steam and the simple principles that govern its proper use. The task is not heavy, nor is a highly technical education or background necessary.

The use of steam for general industrial purposes involves many different applications and a variety of plant, but although each industry has problems peculiar to its own processes and to its own special plant, certain basic principles are common to all, no matter where and how the steam is used.

THE ADVANTAGES OF STEAM

Steam is used to provide heat and power because it possesses many outstanding qualities. For example:

- (a) It gives up its heat at constant temperatures when it condenses.
- (b) It has a very high heat content.
- (c) It is generated from water, which is cheap and plentiful.
- (d) It is clean, odourless and tasteless.
- (e) Its heat can often be used over again.
- (f) It can first generate power and then be used for heating.
- (g) It can be easily controlled and readily distributed.

These qualities cannot be divided sharply from each other; many are inter-dependent.

- (a) Steam gives up its heat at constant temperatures when it condenses.

This property is exceedingly important. It greatly simplifies plant design because counterflow arrangements are seldom needed. It gives complete and simple control of heating operations and enables a heating operation to be exactly repeated.

- (b) Steam has a very high heat content.

This allows a comparatively small steam pipe to carry a great amount of heat. For example, at 200 lb./sq. in. an 8 in. pipe can carry (as steam) all the heat got from burning $2\frac{1}{2}$ tons of coal per hour; at 600 lb./sq. in. the amount would be 7 tons. A hot gas or hot liquid can carry heat in quantity only if it is at a very high temperature that may be quite unsuitable for the process. Steam contains about twenty-five times as much heat as the same weight of air or flue gas at the same temperature. Whereas air or flue gas must drop in temperature to give up any heat, steam at (for example) atmospheric pressure can give up five-sixths of its heat without any drop of temperature.

- (c) Steam is generated from water, which is cheap and plentiful.

To compete with steam the competing substance must be one that can be vaporized and condensed at a temperature approximating to that of boiling water, and as no liquid is cheaper than water the other substance must have better physical properties. No other substance approaches water in its heat-carrying capacity; in fact the other substances that might have a claim are expensive or inflammable, or possess undesirable taste or odour.

- (d) Steam is clean, odourless and tasteless.

This is important in many industries where the steam comes into contact with the processed material, for example, in nearly all food industries and in textile treatment, in dye works, bleacheries, laundries, etc.

- (e) The heat in steam can often be used over again.

When steam is used for evaporating liquids containing water most of the original steam heat is contained in the outgoing vapour. The heat in this vapour can often be used for another heating or evaporating operation, and in appropriate circumstances this process can be repeated five or six times.

- (f) Steam can first generate power and then be used for heating.

This is perhaps steam's most important property. Wherever steam can be generated at reasonably high pressure, and used at moderately low pressure, and where power is required, some or all of the power can be produced by using the highest practical boiler pressure, passing this high pressure steam through an engine or turbine and exhausting at the pressure required for the process.

- (g) Steam can be easily controlled and readily distributed.

All that is needed to control the flow of steam for heating and power is a simple valve, which can be hand-operated or automatically controlled by temperature or pressure. Steam, especially if it is superheated to some extent, can be sent quite long distances in pipes. Provided the pipes are well lagged, and the pressure drop needed to push the steam along can be tolerated, steam can be transmitted economically for several thousand feet when other circumstances are favourable. (E.U.S., Chapter 3.)

PRESSURE

An ordinary pressure gauge not attached to anything shows a zero reading. If, when the gauge is attached to a pipe, it shows 10 lb. per sq. in., that means that the pressure in the pipe is 10 lb. per sq. in. above atmospheric pressure. The pressure of the atmosphere is usually measured by means of a mercury barometer, and the height of the mercury column is taken as the measure of pressure. "Normal" atmospheric pressure is 760 mm., or 29.92 in., of mercury

and is equivalent to 14.7 lb./sq. in. Unless the barometric pressure is abnormally high or abnormally low, the true or "absolute" pressure is the gauge pressure plus 14.7 or (as no industrial pressure gauges are accurate to within a quarter of a pound) 15 for practical purposes.

The ordinary pressure gauge is a somewhat unreliable instrument for measuring pressures below atmospheric pressure—for measuring "vacuum"—though widely used for that purpose. Such pressures are usually spoken of as *inches of vacuum* (which means the amount by which the pressure is below the atmospheric pressure) or as *inches of mercury absolute pressure* (which means the true absolute pressure). For ordinary factory purposes 30 in. of mercury can be taken as equivalent to 15 lb./sq. in. The chemical symbol for mercury, Hg*, is used as a convenient abbreviation. We can thus compare pressures by defining them in four ways:

Gauge pressure : lb./sq. in. <i>g.</i>	..	..	..	10	5	—	—	—	—
Absolute pressure: lb./sq. in. <i>abs.</i>	..	..	..	25	20	15	10	5	0
Absolute pressure: in. Hg.	..	..	..	50	40	30	20	10	0
Vacuum: in. Hg.	..	..	..	..	—	—	0	10	20 30

STEAM FORMATION

When heat is added to water the temperature rises. This rise can be detected by our senses, e.g., the sense of touch; hence this heat is called *sensible heat*. Continued addition of heat raises the water temperature until boiling-point is reached. At ordinary atmospheric pressure water boils at 212° F. If the water is under a higher pressure, the temperature must rise above 212° F. before it will boil; if the water is under reduced pressure, or "vacuum", the water boils below 212° F.

As long as water remains liquid it cannot be colder than 32° F. (except under very great pressure). Steam and water heat quantity calculations are, therefore, based on the assumption that water at 32° F. "has no heat." This assumption is not, of course, true, but the validity of the calculations is not thereby affected. (Every substance in the universe contains heat energy, provided the temperature is above Absolute Zero, —273°C. or —460° F. approx.).

STEAM AND WATER HEAT CALCULATIONS

The standard unit of heat is the British Thermal Unit (B.t.u.), the amount of heat required to raise the temperature of one lb. of water through one Fahrenheit degree at ordinary room temperatures. As the temperature of water is to be raised through 180 Fahrenheit degrees—from 32° F. to 212° F.—it requires 180 heat units, i.e. 180 B.t.u., to raise the temperature of one pound from freezing to boiling-point.

As the specific heat of water (the amount of heat necessary to raise the temperature through one degree) is greater at higher temperatures than at lower temperatures; calculations on sensible heat at much higher temperatures must take this into account. At a pressure of 100 lb./sq. in. the boiling-point of water is 338°F., i.e. 306 deg. F. above freezing-point, but the amount of heat in water at this temperature and pressure is 309 (not 306) B.t.u. because of the higher specific heat at the higher temperatures. Table 1 gives some of these properties of steam and water.

*From *Hydrargyrum*: quicksilver (mercury).

TABLE 1
SOME THERMAL PROPERTIES OF STEAM AND WATER

(a) Pressure : <i>ins vacuum or</i> lb./sq. in. g.	(b) Water boiling temperature ° F.	(c) Sensible heat in water B.t.u./lb.	(d) Latent heat of steam formation B.t.u./lb.	(e) Total heat saturated steam B.t.u./lb.
<i>vacuum</i>				
29.0 in. ..	79	47	1,050	1,096
27.0 in. ..	115	83	1,029	1,112
25.0 in. ..	134	102	1,018	1,120
20.0 in. ..	161	129	1,002	1,131
10.0 in. ..	192	160	983	1,143
<i>atmos. pressure</i>	212	180	971	1,151
100 lb. ..	338	309	882	1,191
200 lb. ..	388	362	833	1,200
420 lb. ..	453	433	772	1,206
1,000 lb. ..	546	545	647	1,192
2,000 lb. ..	637	674	461	1,135
3,192 lb. ..	706	896	0	896

When water kept at any specified pressure is heated to the boiling temperature corresponding to that pressure (as shown in Table 1) any further addition of heat has no effect on the temperature, but turns some of the water into steam. Every B.t.u. added to one pound of water boiling at atmospheric pressure, i.e. at 212° F., converts $\frac{1}{971}$ lb. into steam; thus in order to convert

one lb. of *water* boiling at 212° F. into one lb. of *steam* at 212° F. we must add 971 B.t.u., i.e. $5\frac{1}{2}$ times as much heat as would have heated that pound of water from freezing-point to boiling-point.

All the heat added to change the water into steam causes no rise in temperature; the heat lies hidden in the steam and is called *latent heat*. In order to convert steam back into liquid water this heat must be given up and taken away. It is by giving up its latent heat, when condensing, that steam can be made to heat materials; the process takes place without any change in the temperature of that steam.

Because the latent heat is needed to force the molecules apart, the amount of latent heat involved in this change of physical state is greater at low pressures than at high pressures. The volume of a lb. of steam is different at different pressures; it is very large at low pressures ("high vacuum"), and very small at high pressures. If the pressure is sufficiently high, the volume of the steam is so small that it is actually the same as the volume of the water from which it was produced. At this pressure, called the *critical pressure*, which is about 3,200 lb./sq. in., additional heat changes the water into the same volume of steam without the absorption of any latent heat. This is indicated in Table 1, showing in column (d) the latent heat at various pressures. It will be seen that at the Critical Pressure the latent heat has dropped to zero.

The total heat needed to convert one lb. of water initially at 32° F. into steam at any specified pressure must be:

- (a) The sensible heat needed to bring it to the boil
plus (b) the latent heat needed to convert the boiling water into steam.

This is shown in column (e) of Table 1, from which it will be seen that at about 420 lb./sq. in. the total heat reaches a maximum.

When all the water has been changed into steam, any further addition of heat is shown by a rise in temperature; i.e. it makes the steam hotter—it

superheats it. As the specific heat of steam is only about half of that of water, each B.t.u. added to one lb. of steam raises its temperature by about 2 deg. F., it "gives it 2 deg. F. of superheat." Steam in this condition is called *superheated steam*. Steam that contains no superheat is called *saturated steam*. Steam can contain water either as drops or as an impalpable mist. The water may be due to effervescence in the boiler or to partial condensation. Steam that contains free moisture is called wet steam. Steam that contains neither superheat nor water drops or mist is called *dry saturated steam*.

As the properties of steam cannot be expressed by any simple relations, tables have been compiled giving the properties of steam over a wide range of pressures and temperatures. Abridged steam tables appear as Appendix D. It will be seen that the tables refer to a property called Entropy. This function is a measure of the availability of the heat energy for producing power.

For a fuller discussion of the properties of steam, and for an explanation of Entropy, see E.U.S., Chapters 1, 2 and 3.

WORK DONE BY STEAM

Apart from heating, steam can do mechanical work. The work that steam can do depends on the amount by which the steam can expand. This degree of expansion depends on the machine in which the expansion takes place and the temperature of the steam.

When steam is allowed to expand against a piston or in the nozzles of a turbine, it does work on the piston or the turbine blades and gives up some of its heat energy. As a result it cools down. If it were initially saturated some of it would condense. Condensation in an engine cylinder is very wasteful; condensation in a turbine can cause damage to the blades. On the other hand, if the steam were initially highly superheated, it might still be superheated at exhaust. This could be wasteful. The amount of superheat must be adjusted to the amount of possible expansion. The higher the initial pressure and the lower the exhaust pressure, the more superheat should there be.

Whenever there is *any* superheat in steam fed to a reciprocating engine, the engine cylinder must be lubricated. Engine cylinders can sometimes be lubricated with graphite, which gets over the difficulty of having oily exhaust steam. Difficulties with cylinder lubrication preclude the use of very high pressures, with their appropriate superheats, in reciprocating engines. In a reciprocating engine the extent to which the steam can expand is limited by the size of the low pressure cylinder. In turbines there is no need for lubrication, however great the superheat. There is no limit to the amount by which steam can be allowed to expand in a turbine. The turbine, therefore, can take full advantage of very high pressure highly superheated steam, and can get full benefits from a very high vacuum exhaust. The turbine is not, however, as efficient as a reciprocating engine for powers below about 400 h.p. The reciprocating engine is a very reliable, efficient and easily controlled machine and is recommended for small plants.

By the use of the function entropy it is possible to calculate the amount of energy that an engine or turbine can take out of steam. This amount of energy is called *the heat drop*, and is the difference between the total heat in the inlet steam and the total heat in the outlet steam. In an ideal engine, which would have no losses, this energy that should be available is called the *adiabatic heat drop*.*

The heat that is given to the steam in the boilers is the difference between the heat in the feed water and the total heat in the steam leaving the boiler.

**adiabatic*: 'not passing through' i.e. occurring without heat entering or leaving the system.

The adiabatic heat drop expressed as a percentage of the heat put into the steam gives the *cycle efficiency* for the conditions chosen. The actual amount of the adiabatic heat drop which a real engine or turbine can use varies between just over eighty per cent. for very large machines to below forty per cent. for very small machines.

The statement here given shows the effect, on power output, of various inlet pressures, with two exhaust pressures, when 10,000 lb. of saturated steam are passed through turbines.

Boiler pressure; lb./sq. in. gauge	100	100	200	200	400	400
Exhaust pressure; in. vac. or lb./sq. in. g. ..	20"	20 lb.	20"	20 lb.	20"	20 lb.
Ideal output; kW	637	265	760	403	887	544
Probable actual output; kW	427	122	471	198	532	272

The great effect of change in exhaust pressure on actual output is strikingly illustrated by these figures.

Although the cycles show an increasing efficiency with increased initial pressure, the relation is not practically applicable. A very small turbine working at very high pressure is not so efficient as one of similar power working at moderate pressure. (E.U.S., Chapters 3 and 7.)

The general principles are (a) that power should be generated using the highest available initial pressure and the lowest possible exhaust or back pressure, (b) that there must be enough superheat to suit the conditions and (c) that the larger the machine the more are very high pressures and temperatures justified.

COMBINED POWER AND HEATING

In steam engines and turbines the higher the initial pressure and the lower the exhaust pressure the more power can be produced from each pound of steam. But, however much the limits are extended, the most efficient condensing power station throws away about two-thirds of its heat. The highest efficiency obtained in an orthodox British power station is about 32 per cent. This figure compares very badly with an efficiency of some 80 per cent. obtainable in a modern factory using low pressure steam for process heating. The bad performance of the condensing power station is due entirely to the latent heat of the exhaust steam being thrown away in the condenser.

If, on its way to process heating, steam is passed through an engine or turbine the process becomes the condenser of the power plant and the whole combination can have an efficiency approaching 80 per cent. In order to get the best from the arrangement, the boiler pressure should be as high as conditions permit and the process pressure should be as low as possible. (It will be seen later that there are other benefits to be got from using the lowest possible process pressure.)

The additional heat units needed to raise steam at 200 lb./sq. in. g. instead of 20 lb./sq. in. g. are only 32 B.t.u. per lb. If 10,000 lb. per hour are passed through an engine on the way to process, at least 250 kW. can be generated. The following figures show various conditions such as might be applied to a single Lancashire boiler capable of producing 7,500 lb. steam per hour:

Boiler pressure lb./sq. in. g.	Exhaust or process pressure lb./sq. in. g.	Exhaust temperature ° F.	Power obtainable kW.
95	5	227	150
115	10	239	150
150	15	250	150
200	30	274	150

The subject is discussed at greater length in E.U.S., Chapter 3. The following example is given to show the remarkable savings that can be made.

Assume that a factory requires 45,000–50,000 lb. of process steam per hour at 15 lb./sq. in. *g.*, i.e. approx. 30 lb./sq. in. *a*, and that the electrical load is 1,250–1,300 kW. The technical assumptions are :

Total heat in steam at 200 lb./sq. in. <i>a.</i>	..	..	1,200 B.t.u. per lb.
Adiabatic heat drop to 30 lb./sq. in. <i>a</i>	..	..	145 B.t.u. per lb.
Turbine efficiency, say	..	..	65 per cent.
Real heat drop, 145 × 0.65	..	..	94 B.t.u. per lb.
1 kW. is equivalent to	..	..	3,415 B.t.u.
Power generated by 50,000 lb./hour			
$= 50,000 \times \frac{94}{3,415}$	..	..	i.e. 1,376 kW.

At 94 per cent. generator efficiency, net output is 1,293 kW.
Wetness of exhaust steam 6.2 per cent.
Steam to process after removing wetness .. 47,000 lb./hr.

Comparisons can now be made. Assume that 47,000 lb. of steam will satisfy the process and that 1,280 kW. will meet the power load. As steam at 30 lb./sq. in. *a.* requires some 3 per cent. less heat to be put into it than steam at 200 lb./sq. in. *a.*, it can be assumed that the boiler evaporation will be 3 per cent. better at the lower pressure.

Combined power and heating

Initial steam pressure	..	..	200 lb./sq. in. <i>a.</i>
Process and exhaust steam pressure	..	..	30 lb./sq. in. <i>a.</i>
Steam generated	..	..	50,000 lb./hr.
If the evaporation per lb. of coal is, say, 8 lb.			
(a) Coal burned is	..	..	6,250 lb./hr.

If the steam for Process and Power has been generated separately,

For process steam only

Steam pressure	..	..	30 lb./sq. in. abs.
Steam generated	..	..	47,000 lb./hr.
Evaporation per lb. of coal, say	..	..	8.25 lb.
(b) Coal burned	..	..	5,690 lb./hr.

For power only

Coal burned for power taken from the grid :			
Average, say	..	..	1,700 lb./hr.
Alternatively, coal burned for power at factory, using condensing set	..	..	3,200 lb./hr.
Excess of coal burned for power and process over that required for process only working,			
(a) minus (b)	..	..	560 lb./hr.

44-hour week: 132-hour week:
tons tons

Combined working gives annual saving if power is purchased from the grid	..	1,164	3,492
Combined working gives an annual saving, if power is produced by a factory condensing set	..	2,593	7,779

Such savings can, of course, be secured only if all or most of the exhaust steam is used. Where the whole of the exhaust steam cannot be used in the process, the simple *back pressure* machine just described can be replaced by a *pass-out* machine. In this, most of the steam is passed out at the process pressure at the appropriate point in the machine, the remaining steam needed

to produce the requisite power going through the low pressure end of the machine into a condenser. Some of the many variations and problems associated with combined power and heating are discussed in detail in E.U.S., Chapter 3.

STEAM FOR HEATING

Figure 1 shows in a striking way the distribution of the heat in steam at low and medium pressures. The sensible heat in the water, that is to say, the heat left behind in the condensate after the steam has condensed, rises substantially with increasing pressure. The other striking fact is that the latent heat, i.e. the heat that can be used for heating purposes—decreases as the pressure rises. As a consequence the total heat of saturated steam does not change markedly with increase of pressure.

When steam is used inside a heating surface—coil, pipe, or jacket—the original total heat in the steam is split into its two component parts; (1) the latent heat, which, by passing through the heating surface into the heated material, causes condensation of the steam; (2) the sensible heat, which remains in the condensate. The condensate cannot normally give up any of its sensible heat because it is in contact with steam and is under the same pressure as the steam. Clearly, from the Steam Tables and from Figure 1, the lower the pressure the greater is the latent heat available for heating. This is universally true when steam is used for heating by means of a heating surface. When steam is

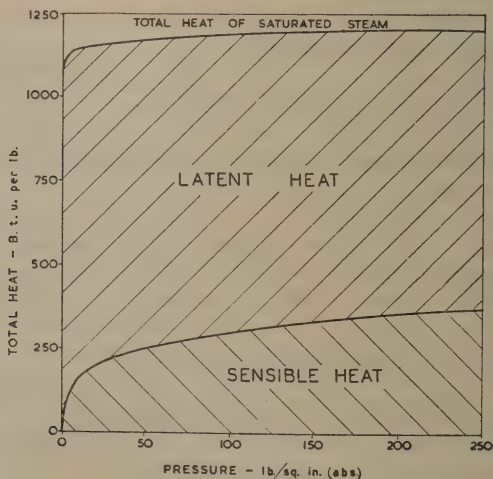


FIG. 1. Distribution of heat in steam at various pressures.

blown directly into or on to the product to be heated, both latent and sensible heats are available, and it might be argued that high pressure steam, having a greater total heat content, might be a better heating medium. Nevertheless, this is seldom true in practice. For direct contact heating, the steam pressure should be as low as is compatible with the requisite temperature and the static head to be overcome in the vat or vessel.

In evaporators or boiling vessels, the temperature of the boiling product depends upon its physical properties and the pressure under which it is boiling. It is quite independent of the temperature of the heating steam. Water in a vat can be made to boil by means of a submerged coil carrying steam at 5 lb./sq. in. g. and having a temperature of 227° F., or it can be heated by

means of a fire at a temperature of $2,270^{\circ}\text{F}$. In both cases the water boils at 212°F ., but it will boil much faster when heat is supplied to it at a high temperature than at a low temperature.

When heat is used to heat a non-boiling product, there is no such automatic temperature control. The pressure of heating steam must be suited to the temperature called for by the products. Thus the sterilization of milk, the vulcanization of rubber and the moulding of plastics demand certain prescribed temperatures. If they are not reached, or if they are appreciably exceeded, material will be spoilt.

When steam is used to heat a flowing substance, the temperature of the steam must depend upon the rate of heat transfer, which depends upon many variables and is discussed below (**HEAT TRANSFER**, page 408).

SUPERHEATED STEAM FOR PROCESS HEATING

The object of steam-heated process plant is to transfer heat from the steam to the material being processed. The temperature of the processed material must often be accurately held within narrow limits. When heat is lost locally from a fluid (i.e., a liquid or a non-condensing gas), for example at the walls of a heating surface, a temperature gradient occurs in the fluid from its centre to the heat-transmitting surface. There is a time interval between the extraction of heat at one point on the surface and its replacement from the interior of the fluid. This time lag is related to the thermal conductivity of the heating medium, which, for gases, is very low. In practice, diffusion and convection both lessen the temperature gradient, but if there is a gradient, heat transfer must clearly be slower than in any system that has no temperature gradient. Superheated steam is a gas and behaves like other gases until it has lost all its superheat.

The extraction of heat from saturated steam does not involve any temperature gradient through any part of the steam. The steam remains at saturated temperature while it is parting with its latent heat and condensing to form water. As it condenses, it is simultaneously replaced by new steam, still at saturated temperatures. There is a flow of steam to the heating surface, not a flow of heat.

Although there are some occasional exceptions, experience generally shows that superheat not only is useless in most process heating but is usually disadvantageous. Superheated steam supplied at one end of a long coil, and discharging condensate at the other will part with less heat in the first half than in the second. The portion of the coil containing superheated steam transmits less heat for perhaps quite a large temperature drop than that part of the coil where a very small drop releases the whole of the latent heat of the steam. Where the steam space is large and the steam path short, as in some calandrias, superheated steam can sometimes be used without any lowered heat transfer, provided the degree of superheat is not too great. As soon as the steam in contact with the heating surface has given up its superheat there will be a film of condensate on the heating surface. New steam flowing in to take the place of the condensing steam will instantly part with its superheat by re-evaporating some of that condensate film. (E.U.S., Chapters 1 and 5.)

SUPERHEATED STEAM FOR POWER GENERATION

It has been explained that when steam gives up some of its heat energy, to do useful expansion work in an engine or turbine, it loses heat, cools and, unless appropriately superheated, must partly condense. Apart from being wasteful, condensation can be harmful in a reciprocating engine, and in a

turbine water droplets will wear away the blades, if there is more than about 13 per cent. of moisture at exhaust. In a reciprocating engine, condensation in the cylinder can account for the biggest loss. During the exhaust stroke the cylinder contains steam at exhaust pressure and temperature. The cylinder, piston, steam ports and passages are all giving up heat to the exhaust steam. At the end of the exhaust stroke, the temperature of the metal may have dropped to nearly that of the exhaust steam. When the admission valve opens, the hot steam has first to heat up the steam passages, ports, piston, and cylinder head, and unless the steam is superheated some must condense. After cut-off, work-producing expansion takes place, with a further loss of heat and more condensation. When the exhaust valve opens, there may be quite a lot of water in the cylinder. The drop in pressure at release flashes steam from the water. The presence of water speeds up the loss of heat from the metal as the hot metal readily boils off the condensate. By using sufficient superheat, cylinder condensation can be entirely eliminated. If the steam remains superheated right down to exhaust point, the cylinder metal remains at a much more even temperature because the superheated steam only reluctantly parts with and absorbs heat. The introduction of superheat for reciprocating engines was the biggest single improvement since James Watt's invention of the separate condenser.

The amount of superheat that should be given to the steam that is feeding an engine or turbine is fairly simply estimated.

- (a) In a reciprocating engine exhausting to a condenser, there should be enough superheat to ensure dry steam at exhaust.
- (b) In a turbine exhausting to a condenser, there should be enough superheat to prevent the wetness of steam at exhaust exceeding about 13 per cent.
- (c) In a reciprocating engine or turbine exhausting into a process steam main, there should be enough superheat to allow the exhaust steam to enter the process main slightly superheated, so that on arrival at its point of use it will be as nearly dry saturated as is possible.
- (d) In a reciprocating steam engine exhausting to a process where the steam comes into contact with a product that must not be contaminated by oil, there must be no superheat, because superheat calls for cylinder lubrication. (E.U.S., Chapters 2 and 7.)

WIREDRAWING

If steam is allowed to expand through a valve or orifice it does no external work and therefore loses no heat energy. Suppose a factory raises steam to 200 lb./sq. in. *g.* superheated to 500° F. and passes the steam through an engine exhausting to process at 30 lb./sq. in. There may be occasions when the amount of exhaust steam is insufficient, and live 200 lb./sq. in. steam must be blown through a reducing valve into the process main at 30 lb./sq. in. From the Steam Table the total heat of 200 lb./sq. in. steam at 500° F. is 1,267 B.t.u. per lb. Saturated steam at 30 lb./sq. in. has a total heat of 1,173 B.t.u. per lb. but the steam that has expanded to 30 lb./sq. in. pressure has 1,267 B.t.u. per lb. and, therefore, contains (1,267 minus 1,173) i.e. 94 B.t.u. per lb. of surplus heat. This cannot escape; it must therefore superheat the steam. Taking the specific heat of steam as 0.5, there will be a superheat of 188° F. so the steam temperature will be (274 plus 188), i.e. 462° F. (Interpolation in the superheat table gives a value of 464° F. because the specific heat at these pressures is actually less than 0.5.)

Expansion through an orifice where no work is done is called *wiredrawing*. Steam from a reducing valve or a partly open stop valve is always to some

extent wiredrawn. If the steam were wet before expansion, the wiredrawing would evaporate some of the moisture and thus dry the steam or partly dry it instead of superheating it.

If medium pressure steam at, say, 50 lb./sq. in. is dry saturated and is used for heating water by means of blowers in a tank or a vat, there is only the hydrostatic pressure of say 2 lb./sq. in. about 4 ft. below the surface at the blower outlet. This means that the steam will be wiredrawn in the blower and superheated by over 50 deg. F. Unless the blower is a good one, there is a strong possibility that the steam bubbles will not have time to give up their superheat and to condense completely before breaking the surface. Steam used for direct injection should always be used at the lowest possible pressure and be without superheat.

DE-SUPERHEATING

As has been shown earlier in this chapter, it is nearly always undesirable to use superheated steam for heating, whether indirectly through a heating surface or directly by injection. It may therefore be desirable to pass superheated steam through a *de-superheater* where the steam meets a spray of distilled water. The superheat gives itself up by evaporating some of the water. In the case considered in the section on Wiredrawing, the amount of superheat energy released by wiredrawing was 94 B.t.u. per lb. Suppose this is to be removed in de-superheating. The latent heat of steam at 30 lb./sq. in. is 930 B.t.u. per lb., so that each lb. of wiredrawn steam will evaporate $\frac{94}{930}$ lb.

i.e. 0.101 lb. of water. This will increase the amount of steam leaving the de-superheater by 10.1 per cent., provided the de-superheating water was at boiling-point.

SELECTION OF BOILER PRESSURE

Broadly speaking, steam for power generation should be used at as high a pressure as other conditions will allow. The larger the installation, the higher can be the pressure. For process purposes the steam should be used at as low a pressure as possible, and should be generated in the boiler at as low a pressure as is consistent with reasonably cheap pipe distribution. For combined power and heating, the steam should be generated at the highest practical boiler pressure and used at the lowest possible process pressure.

STEAM FOR PROCESS

Process heating can be divided into the following broad groups:

1. Evaporation by means of heating surface
 - (a) calandria type, in which the heating steam is on the outside of the tubes and the liquid to be boiled is inside the tubes;
 - (b) coil or worm type, where the steam is inside the tube and the boiling material outside—the tubes are often relatively long;
 - (c) shell or jacket type, where the steam is inside a cylinder whose exterior heats the material, ironers, calenders, etc.; where the steam surrounds the vessel in a jacket, boiling pans, etc.
2. Raising the temperature of the process substance by
 - (a) heating surface;
 - (b) direct contact.
3. Maintaining the temperature of the process substance by
 - (a) heating surface,
 - (b) direct contact,
 - (i) To make good losses by radiation, etc.
 - (ii) To make good heat absorbed by endothermic action.
 - (iii) To effect a curing or conditioning of the material.

4. Distillation by open steam.

(a) for fractional distillation. (b) for deodorizing fats, etc.

1, 2, and 3 all have heat transfer as their main problem; only 4, steam distillation, is different because heat transfer is not the important point.

STEAM DISTILLATION

Open steam blown into a liquid is often used for distillation. When steam is blown through a liquid of much higher boiling point than water, the steam and the distillate both exert a vapour pressure and the liquid boils when the sum of the two vapour pressures equals the external pressure. Substances with high boiling points may thus be distilled at relatively low temperatures. Aniline, for example, boils at 356° F. at atmospheric pressure, but will distil at the same pressure in a current of steam at 210° F. Steam distillation yields a condensate consisting of water and the distilled product or products in proportions dependent on their respective vapour pressures and molecular weights.

Examples of steam distillation are:

stripping of crude benzole from wash oil in the carbonization industries, deodorization of fats in the food industry, etc.

It is particularly useful in processing materials that are liable to decomposition or spoiling at temperatures near their normal boiling points.

HEAT TRANSFER

Steam is used in many processes for providing heat. By far the greatest use of steam for this purpose is through some kind of heating surface. In all such plants the heat of the steam must be transferred from the *steam side* through the heating surface wall to the *material side*. The general principles of heat transfer are discussed in Chapter 9. Only heat transfer as it affects steam is dealt with here. The whole subject is dealt with in greater detail in E.U.S., Chapter 11.

The rate of heat transfer through a heating surface from the steam to the material that is to be heated depends on the following:

The temperature difference between the steam and the material.

The actual temperature.

The area of the heating surface.

The thickness and composition of the heating surface.

The heat-resistant films on the heating surface.

The movement of the steam.

The movement of the material.

Effect of Temperature on Heat Transfer

For all practical purposes the rate of heat transfer can be taken to vary directly with the temperature difference between the steam and the heated product. This, of course, is one of the limitations on the use of low pressure steam. But the other advantages of low pressure steam are so great that every effort must be made to improve conditions so that low pressure steam *can* be used.

The higher the actual temperature at which the transfer of heat takes place, the faster is the rate of heat transfer. But many products—milk, sugar, hormone extracts, etc.—deteriorate if the process temperature rises above particular limits, so unless the heating operation can be done very quickly advantage cannot always be taken of this property.

Area and Nature of Heating Surface

At first thought it would seem obvious that a heating coil twice the area of another would transfer heat twice as fast, at the same temperature. But this is true only up to a point. When a liquid is being heated, the heat transfer

will be slow unless the heated material is in brisk movement. In an endeavour to improve heat transfer by increasing the area of the heating surface, the arrangement of heating pipes and coils sometimes become so complicated that the natural circulation of the material is impeded to such an extent that the total heat transfer is actually reduced. As far as possible, the heating surface should be smooth and streamlined to promote easy circulation of the heated material.

The heat conductivities of metals vary greatly, but heat transfer through a metal is so vastly greater than heat transfer through the heat-resistant films on metal surfaces that, for all practical purposes, the nature of the metal can be ignored.

Heat-Resistant Films

There are always films on both sides of any heating surface, and as it is these films that offer the greater amount of the resistance to heat transfer, everything possible must be done to reduce them, even though we can seldom hope to eliminate any of them completely. The following films are present to a greater or lesser degree :

- (a) *On the Steam Side:*
 - Air or non-condensable gas film.
 - Condensate film.
 - Tarnish, mill scale or oxide film.
- (b) *On the Material Side:*
 - Dirt or scale film.
 - Stagnant material film.

The heat passing from the steam to the material has to pass through all these films. The following figures show what a severe obstacle any non-metallic film offers to heat transfer:

Substance	Heat transfer coefficient*	Relative resistance to heat transfer
Copper	2,664	1.0
Steel	312	8.55
Boiler scale ..	0.5 to 15	177 to 5,300
Water } not in	4	665
Air } motion	0.22	12,100

*B.t.u./sq.ft. hr. deg. F./in. (see Chapter 9).

It will be seen that a static film of air is over 12,000 times more resistant to the transfer of heat than a piece of copper of the same thickness; similarly, a film of boiler scale may be from about 200 to over 5,000 times as resistant as copper, or from about 20 to over 500 times as resistant as the steel of which the boiler is made.

The Stagnant Material Film

Most non-metallic materials are poor conductors of heat, and unless the film or layer of material in contact with the heating surface is constantly disturbed, e.g. by a quick flow or vigorous circulation, heat transfer may be very slow. It may be assumed that doubling the speed of movement or circulation of the heated material will increase the rate of heat transfer by rather more than 25 per cent. In evaporators, adequate circulation can usually be obtained by good design, but in simple heating it may be necessary to adopt mechanical circulation by stirrer or pump.

In evaporators, if the circulation is sluggish (owing, for example, to working the evaporator below its rated capacity) the lower layers of liquid can become greatly overheated. This is because the hydrostatic head of the liquid raises the boiling-point of the liquid at the bottom of the vessel above the actual

temperature at which the liquid on the surface is boiling. The material side of the heating surface must be regularly cleaned, and the plant must be designed to make this easy (E.U.S., Chapters 11 and 12).

The Dirt or Scale Film

Dirt or scale often adheres to the material side of the heating surface. Many liquids—particularly water—deposit scale when heated or boiled. Air heaters collect dust and fluff, which are excellent insulators. It is important, therefore, not only to clean the material side of the heating surface regularly, but to make sure, when installing the plant, that the design makes proper cleaning not only possible but easy.

Tarnish, Mill Scale or Oxide on the Steam Side

It is not generally possible to inspect, much less to clean, the steam side of the heating surface, but a clean internal surface contributes materially to efficient heat transfer.

Condensate Film

The amount of condensate formed on the steam side of a heating surface depends not only on the rate of condensation of the steam but also on the amount of moisture in the steam and the ease with which the condensate film can run off. Steam can contain moisture for any of the following reasons:

Priming or carry-over in the boiler; saturated steam losing heat in the steam pipe; heat removed from steam by an engine or turbine in producing useful power; cylinder condensation in a reciprocating engine, due to lack of sufficient superheat.

A combination of these conditions can easily cause steam to reach process plant with 30–40 per cent. (in extreme cases, at the end of a long pipe, 75 per cent.) of moisture. Wet steam should, if possible, be dried before being put into process plant.

Steam driers usually consist of small vessels in which the steam is made to change direction quickly so that the moisture impinges on the walls, down which it runs to a collecting sump and draining arrangement.

If wet steam condenses on a heating surface it overloads the surface with moisture and impedes heat transfer.

If the velocity of the steam can be kept high, and if the direction of steam flow can follow the natural draining path of the condensate, the condensate film can be reduced. High steam velocity alone helps to brush off the condensate film, and keeps any remaining film turbulent. This brushing effect is particularly important in horizontal or nearly horizontal pipes.

AIR AND ITS REMOVAL

When steam is shut off and the plant cools down, the steam inside condenses forms a vacuum, and draws air in through all the tiny leaks at joints and glands that are invisible or ignored when the plant is under pressure. When the steam is turned on again, air or any other uncondensable gas mixes with the steam, or blocks the flow of the steam, unless the air can escape. Apart from this air that gets into the plant at shut-down, steam generally contains air or CO_2 expelled from the boiler feed water unless it has been most carefully de-aerated.

When steam condenses on a heating surface in a piece of plant, the air cannot condense and the steam flowing on to the walls of the surface to take the place of the condensed steam builds up a blanket or film of air between the body of the steam and the condensate film. Apart from this insulating effect, the air mixed with the steam lowers the temperature of the steam. This is because the temperature of the steam depends on its partial pressure. If a mixture of

steam and air at a pressure of 30 lb./sq. in. *abs.* contains one part by volume of air to two parts of steam, the air will exert a partial pressure of 10 lb./sq. in. *abs.* and the steam a partial pressure of 20 lb./sq. in. *abs.* Now the heat in the mixture is provided by the steam, so the temperature of the mixture is due to the steam which has a true (partial) pressure of only 20 lb./sq. in. *abs.* The temperature will thus be only 228° F. instead of the 250° F. that would be inferred from the pressure gauge reading of 15 lb./sq. in. *g.* (30 lb./sq. in. *abs.*). In order to maintain output under such conditions, either a wastefully high pressure must be used or the air must be removed.

Air can be removed by open vents, hand-operated cocks or automatic venting valves.

Quite commonly no provision whatever is made for removing air. This is most reprehensible. Every piece of steam-heated plant must be provided with adequate means for removing air from the steam space. In some plants, hand-operated cocks are provided. If the operator is conscientious, and not too busy, these can have a limited degree of usefulness. The cocks should be wide open at the start-up and should be allowed to blow lustily for some time. The cocks should then be partly closed to prevent undue waste of steam, but they should be sufficiently open to show a definite blow of steam. Unfortunately, hand-operated cocks are very often neglected and are either full open (with waste of steam) or left shut (with loss of output due to air blanketing). However conscientious the operator, he cannot tell merely by inspection how far open the air cocks should be.

If there are several steam pressures in the factory, the plant working at high pressure can be fitted with permanently open air vents piped into a lower pressure main. This gives very satisfactory results in the high pressure plant but makes the task of properly venting the low pressure plant all the more important.

Automatic air vents give excellent service, but they must be examined regularly and maintained properly. Their action is described in the later section on Traps. They consist of thermostatic valves so adjusted that they close at steam temperature and open when the temperature falls below the predetermined temperature.

It is, however, useless to fit good air vents unless they are fitted in the right places, and many pieces of plant have no "right place." All steam-heated plant should be so designed that the steam is made to follow a definite path to a point remote from the steam inlet. The air will then be driven to this remote point, and that is the place for the air vent. "Remote" has nothing to do with the linear distance from the steam inlet, but for this purpose means the end of the steam's journey. (See E.U.S., Chapters 10, 12, 13, and "Steam Trapping and Air Venting", by L. G. Northcroft².)

MOVEMENT OF THE STEAM

The beneficial effects of movement of the steam have already been stressed, because it is only by movement that the air can be driven to a remote point for venting; steam movement makes the condensate film turbulent and helps to brush it off the surface.

There are, however, some pieces of plant in which little or no movement normally takes place and where it is difficult to induce movement. Examples are: moulding presses; tentering machines; autoclaves; some laundry ironer beds. Benefit can sometimes be gained in such cases by moving the steam artificially as, for example, by supplying it at considerably higher pressure than that at which the plant normally works. The inlet valve to the plant is formed like an injector, the plant being arranged for a through flow of steam. The

outlet from the plant is piped back to the suction side of the injector, a pot or separator is fitted in the outlet return pipe from which the air is vented and the condensate is drained. This method of steam circulation cannot be applied successfully to all sluggish plants but, where circumstances permit, a marked improvement can be secured.

CONDENSATE REMOVAL

The condensate resulting from the condensation of steam on to a heating surface, having been kept to a minimum by supplying the plant with dry steam and having been made to leave the heating surface as quickly as possible, must be drained from the inside of the heating surface so that it does not waterlog the plant and prevent access of steam to the surfaces. This draining must be done in such a way that only the water is removed; steam must not accompany the water and be thus wasted.

Far too many plants are fitted with hand-operated drain valves or cocks. These are meant to be kept wide open at the start and, after the initial rush of condensate, to be closed down into a "cracked open" position that will just pass the condensate yet will not blow steam. Quite apart from the fact that operators are generally too much occupied to be sufficiently careful about the setting of the drain cock, the cock simply cannot in practice be so set that it just passes the condensate without either blowing steam or holding back water.

The only way to keep a steam space clear of condensate without waste of steam or risk of waterlogging is by the use of a device which automatically releases the condensate and traps the steam. That device is the Steam Trap.

STEAM TRAPS

The function of a steam trap is to distinguish between water and steam, to open a valve to allow the water to pass but to close the valve to prevent steam from passing. There are two main types of trap, the mechanical trap and the expansion trap. Mechanical traps distinguish between water and steam by means of density differences, for example, by a float that floats in water and sinks in steam, or a floating bucket that sinks when full of water and rises when full of steam. Expansion traps work by virtue of the fact that water can be cooler than steam at the same pressure. Clearly this very principle on which the action of expansion traps depend puts them at some (albeit small) disadvantage, because the expansion traps cannot respond to the presence of water until the water has had a chance to cool a little.

Mechanical traps discharge condensate immediately without holding back water in the heating surface. Float traps discharge continuously, bucket traps intermittently. Mechanical traps discharge condensate at the saturation temperature. The inverted bucket trap cannot become air-locked as it is inherently air discharging, but the open bucket trap and the float trap can become air-locked and stop working unless they are fitted with special means for removing air. Bucket traps are more robust than float traps and can withstand occasional water hammer; they have no float to collapse or puncture. It is possible—though the right conditions are seldom met with—for an inverted bucket trap to lose its water seal and blow steam. If it does so, it cannot correct itself without outside help. Only the mechanical traps are suitable for handling really large quantities of condensate. The valve areas in mechanical traps must be suited to the pressure at which the traps are to act.

There are two kinds of expansion traps, the plain expansion trap and the balanced pressure expansion trap. Plain expansion traps are simple thermostats. The expansion element, a long metal tube, bi-metallic strip or a bellows filled with a liquid of high boiling-point, expands and closes the valve at a

certain definite pre-selected temperature. It follows, from this, that this kind of trap is not suited to working with varying pressures, but must be set exactly for one pressure. These expansion traps are very simple and robust and can withstand ill-treatment and water hammer.

The balanced pressure expansion trap consists of a bellows partly filled with a liquid whose boiling-point is just below that of water. When this trap is fitted to a steam space the pressure of the steam is acting on the outside of the bellows and the vapour pressure of the liquid is acting inside the bellows. When the temperature is such that the liquid inside the bellows boils, the bellows expands and closes the valve. This kind of trap thus works independently of the steam pressure or temperature. Its action depends on *the relation between the temperature and the pressure*. Its balanced condition is, however, entirely upset if superheated steam gains access. Superheated steam will cause an excessive internal pressure to be generated that will probably damage the bellows.

Expansion traps, particularly those of the balanced pressure type, are the devices used as automatic air vents for steam spaces. Those of the balanced pressure type are the most suitable as they are self-adjusting, but they must not be used where there is any chance of their coming into contact with superheated steam.

Steam traps are often situated in alleys and yards. When plant is shut down, mechanical traps all close their valves automatically; expansion traps open their valves. Consequently, in frosty weather mechanical traps are much more likely to be damaged by ice formation than expansion traps.

Traps are not merely hardware or ironmongery. For every piece of steam-heated plant there is one particular kind of trap that best suits its requirements. A good piece of plant fitted with a first-class trap may be quite unsatisfactory if the trap does not suit the conditions. Not only can the wrong kind of trap be fitted the right way, but the right kind of trap can be fitted the wrong way. The most common faults are: (a) fitting a mechanical trap too far away from the plant it drains (this can result in steam-locking), and (b) using one trap to drain several pieces of plant (this will cause water-logging).

For a fuller treatment of this subject see E.U.S., Chapters 8 and 9, and "Steam Trapping and Air Venting"², which the reader is advised to consult before choosing and fitting steam traps.

PIPE DRAINING

Unless pipes are properly drained, steam cannot reach the plant it is feeding in a dry state. If much water is allowed to collect in a pipe, serious water hammer may occur. In most factories pipe draining is done in a most haphazard way. If a steam pipe is to be kept really free from water, the only sure way is to fit a full-size tee-piece or other full-bore collecting pot into which the water is certain to fall; once it is in the pocket, a trap can remove it. Small pipes screwed into the bottom of the main seldom or never remove water until it is present in dangerous amounts; water flying along a pipe at perhaps 70 to 90 m.p.h. just jumps across a small pipe.

REMOVAL OF CONDENSATE FROM STEAM SPACES UNDER VACUUM

The most common case where condensate must be removed from a space under vacuum is an ordinary surface condenser. Various kinds of pump are available for extracting such condensate. In some cases the pump also combines the function of a vacuum pump. Where the heating or cooling surface is at a sufficient height, by far the best and simplest way is to run the condensate out through a barometric leg sealed in an atmospheric tank. The atmo-

spheric tank must be drained by an overflow so placed that there is always enough water in the tank to fill the barometric pipe completely to ensure that at starting-up the seal in the tank cannot be broken and the vacuum lost. The barometric leg should always be a few feet longer than the height corresponding to the desired vacuum.

CONDENSATE RETURN

The right kind of traps having been fitted to the plant, in the right way, the condensate has now to be dealt with. If it is discharged reasonably near the boiler house, its obvious destination is boiler feed, because it is pure distilled water. If it is too far away from the boiler to justify piping it back, some better use for it can surely be found than running it down the drain—a fate it suffers only too often. Can it be used locally for process purposes? Can it be hot water for canteen or lavatories?

If it is to be used for boiler feed it is generally collected in a tank called a *hot well*, from which the boiler feed pump draws its supply. A pump will not lift or suck up very hot water because the reduction in pressure causes a flash of steam which breaks the suction. In order to keep the hot well cool enough to permit the pump suction to operate, cold water has often to be run in, at the wasteful expense, of course, of good distilled condensate. Table 2 shows the suction lift or pressure head that the *hot tank* should have below or above the pump inlet.

TABLE 2

<i>Temperature of water ° F.</i>	<i>Maximum suction lift Feet</i>	<i>Minimum pressure head Feet</i>
130	10	—
150	7	—
170	2	—
175	level	level
190	—	5
200	—	10
210	—	15
212	—	17

Most traps will discharge condensate to a height above the trap outlet. This height depends on the pressure of steam inside the trap driving the water out. It is possible to raise water 2 ft. for every lb./sq. in. *g.* inside the trap. Condensate that can be raised in this way can be put into a tank set well above the boiler feed pump. But not all condensate can be lifted in this way. Under no circumstances must traps draining steam mains be allowed to discharge their condensate above their own level lest dangerous water hammer be induced at the start-up, when condensate is heavy and the pressure may be insufficient to lift the condensate. Generally speaking, it is not the best practice to lift the condensate above the trap outlet, but there are occasions when it is convenient to do so and, apart from the draining of steam pipes, there is generally little risk in doing so.

If the traps discharge at low level, the condensate must be raised by pump or by other means to the high level tank. If a pump is used, a flash of steam can cause the suction to fail, but this is not so important as temporary failure of the boiler feed pump. It is possible to get pumps provided with special large suction inlets for pumping hot water.

LIFTING TRAPS

Technically, a lifting or return trap is not a trap, but a pistonless pump. Inside the body of the pump is a float operating the valve gear. When the float is low, water can run into the trap by gravity through a non-return valve. When the trap fills, the float trips the valve and allows the steam supply to blow the trap's contents through a non-return valve to an elevated tank. When the float falls, because of the trap emptying, it cuts off the steam supply and opens a release valve which blows off the steam pressure in the trap. The exhaust steam from the trap can be blown into the water in the tank or sent to any other convenient destination. If the exhaust from the trap is merely discharged to atmosphere, a lifting trap can be very wasteful.

A lifting trap can be used to remove condensate from a heating surface under vacuum, the exhaust steam being returned to the heating surface. It is a very wasteful device for use in draining a condenser.

FLASH STEAM

The temperature of the hot water leaving a steam trap will be at or just below the water boiling-point corresponding to the pressure. If a piece of plant is supplied with steam at 100 lb. sq. in. *g.* the condensate will be discharged from the trap at about 338° F.—the boiling-point corresponding to that pressure. Table 1 shows that this water will contain about 309 B.t.u./lb. If it is discharged into a tank at atmospheric pressure some of it must at once boil off, using up latent heat until the temperature has fallen to 212° F.—the boiling-point at atmospheric pressure. It must get rid of 309–180, i.e. 129 B.t.u. of surplus heat; a “flash” of steam is the inevitable result. As the latent heat of steam at atmospheric pressure is 970 B.t.u./lb., the amount of flash steam produced will be 129/970, i.e. 0.133 lb. per lb. of condensate.

A loss of flash steam occurs whenever a steam trap discharges condensate; the higher the pressure, the greater the flash. Loss of flash heat can be avoided in several ways:

the water can be passed through a heat exchanger before being discharged at lower pressure,

the flash from high pressure condensate can be piped to a low pressure main, the flash steam at atmospheric pressure can be used to heat water.

Table 3 shows the amount of flash steam produced when water at various pressures and temperatures is discharged to lower pressures.

TABLE 3

Original hot water		Per cent. of water flashed when pressure reduced to:			
Pressure lb./sq. in. <i>g.</i>	Temperature ° F.	40 lb./sq. in. <i>g.</i>	20 lb./sq. in. <i>g.</i>	10 lb./sq. in. <i>g.</i>	Atmos.
200	388	11.5	14.3	16.2	18.7
150	366	9.0	11.8	13.7	16.3
100	338	5.8	8.7	10.6	13.3
80	324	4.2	7.1	9.1	11.8
60	307	2.3	5.3	7.3	10.0
40	287	—	3.0	5.3	7.8
20	260	—	—	2.1	4.9
10	239	—	—	—	2.9
0	212	—	—	—	—

FLASH TANKS

When it is known that flash steam will be produced, it is advisable to lead the hot water into a flash pot or tank where the flash steam can disengage itself from the water. If the flash is from a high pressure plant and the flash steam is piped to a low pressure main, the flash tank will have to be fitted with a float valve controlling the water outlet, to prevent its being blown empty; or a large trap can be used. When the flash is to take place at virtually atmospheric pressure, the flash tank can be a small pot made out of any odd length of large diameter pipe.

It is impossible to lay down precise rules for the sizes of flash tanks, but limits can be stated thus:

Low Limit

The flash tank should never be so small that the velocity of the flash steam exceeds 10 ft. per sec.

High Limit

The flash tank need never be larger than one whose cross-sectional area in sq. ft. equals $\frac{\text{lb. per hr. of flash steam}}{3 \times \text{absolute pressure}}$

BLOW-DOWN FLASH

Boiler blow-down, especially from high pressure boilers, contains a great deal of flash heat. For example, each pound of blow-down from a boiler working at 250 lb./sq. in. *g.* contains 200 B.t.u. more than it can hold at atmospheric pressure. This will cause 20 per cent. of the blow-down to be flashed off as steam. If the blow-down amounts to 5 per cent. of the water fed into the boiler, the flash from the blow-down, unless it is recovered and used, represents a loss of 1 per cent. of the steam output of the boiler. If the blow-down is intermittent, it is difficult to arrange for flash recovery, but if continuous blow-down can be arranged (and this is generally desirable) various means are available for recovering the flash heat (E.U.S., Chapter 14).

FLASH COOLING

Suppose there is a dilute process liquor at 200° F. and that the next process requires it to have a temperature of 150° F. An elegant way of cooling it is to spray it into an empty vessel connected to a condenser and a vacuum pump. The Steam Table tells us that if the vacuum is maintained at 22.5 in. the liquid will boil at 150° F. It will, therefore, flash off its surplus heat and lower its temperature instantly from 200° F. to 150° F. The Steam Table shows that the surplus heat will be 168 *minus* 117, i.e. 51 B.t.u./lb. The latent heat of steam at 22 in. vac. is 1,008 B.t.u./lb., so $\frac{51}{1,008}$ i.e. 0.05 lb. of steam will be flashed off from each lb. of liquor, which may save subsequent evaporation, and if the condenser takes the form of some kind of process heater, the heat can all be recovered.

RECOVERING FLASH HEAT

The best and simplest way of recovering and using the heat in flash steam is to duct it into a spray condenser or contact heater. This is simply a large diameter pipe down which water or process liquor is sprayed. The water used can be boiler feed water, process water, central heating water, etc. (See E.U.S., Chapter 14.)

MULTIPLE EFFECT EVAPORATION

In evaporation by steam heat, only the latent heat of the heating steam is transferred to the product being evaporated. This heat is absorbed :

(a) as sensible heat, to raise the temperature of the product to boiling-point, and (b) as latent heat, for evaporating liquid from the heated product.

The vapour from the product is at lower pressure and temperature than the original steam, but it holds all the heat of the original steam *less* the sensible or water heat left behind in the condensate, and any sensible heat that has been used to bring the product to the boil.

If there is a use for this vapour at its pressure and temperature, it can be used in the same way as steam newly generated in a boiler. It can be used for process heating, water heating or space heating; or it can be used for evaporating water from another product or from the same product from which it sprang. Such a second evaporation must be done at a lower pressure than the first evaporation; in this case also the heat in the vapour will divide itself into latent heat transferred to the product, and sensible heat retained in the condensate.

Provided pressures and temperatures are suitable, this process of passing the latent heat on and on can be continued until the pressures and temperatures are too low for effective heat transfer. At each stage the sensible heat is retained in the condensate. Much of the condensate heat can be recovered as flash and brought back into the cycle, but flash heat in condensate is one of the principal limiting factors.

This successive use of the same heat for evaporation is called the Multiple Effect Principle and has reached its highest stage of development in the beet sugar industry where, although the principal heat requirement in the process is evaporation, the evaporation is done virtually for nothing. The efficiency expressed as the heat used in evaporation in relation to the heat input may well exceed 500 per cent. (See E.U.S., Chapter 17.)

Many kinds of refinements can be applied to a Multiple Effect Evaporator so as to improve its efficiency.

THERMO-COMPRESSSION

Latent heat can be re-used in another way, by boosting low pressure vapour or exhaust steam up to a slightly higher pressure by mixing it with high pressure steam in an injector; alternatively, low pressure steam can be boosted by a mechanical compressor or turbo-blower. The mechanical compressor is particularly suitable where fuel is expensive and power is cheap—as in Switzerland.

Thermo-compression, whether by injector or compressor, is of limited specialized application and can be done successfully only where the pressures differ little from atmospheric pressure and where only a very small degree of compression is attempted. Under these conditions, most striking results have been obtained.

HEATING BY DIRECT STEAM INJECTION

Where a material can be heated without there being any objection to the addition of a small amount of water, the direct injection of steam is the cheapest, simplest and most efficient way. All that is needed is a "blower" of "injector" supplied with low pressure steam. It is important that the steam supply be really low in pressure and without superheat, otherwise much of the steam may break the surface of the liquid and be lost.

It is also important that the blower be well designed, otherwise the steam and the water will not mix properly. With a bad blower much steam can be

wasted and the tank or vat may suffer bangings and rattlings which will soon produce leaks or may even crack the plates of the vessel.

Direct injection eliminates the need for traps and condensate collection, but of course the fact that the condensate has been put into the heated product means that more boiler-feed make-up water must be provided and treated.

Unless direct injection is properly carried out it may result in waste, in excessive maintenance and in extra boiler scale. Properly carried out, it is a very good way of heating watery liquids. Not only is the latent heat added to the product, but the whole of the sensible heat as well.

THE EFFICIENT USE OF STEAM

The following few simple precepts govern the efficient use of steam:

- (a) Prevent the escape of heat.
- (b) Reduce the work to be done by heat.
- (c) Use the heat over again.
- (d) If it can be avoided, never allow steam at high pressure to expand to a lower pressure without getting something useful from the expansion.

The dividing line between some of these precepts is not always clear, but that does not matter. Let us examine some of these points more closely.

(a) Preventing the escape of heat

This means attention to such matters as:

- | | |
|---------------------|------------------------------|
| Safety valve blows. | Waste of condensate. |
| Lagging. | Waste of flash. |
| Leaks. | Excessive blow-down. |
| By-passed traps. | Overflowing hot water tanks. |

(b) Reducing the work to be done

by such means as:

- Mechanical removal of water before drying.
- Re-circulation of drying medium, e.g. air.
- Lowering of process temperatures.
- Reduction of re-processing by reducing the amount of work spoilt in process.
- Quick processing.
- Reducing amount of added water that must eventually be evaporated.
- Processing at lower water content.
- Shutting doors and mending broken windows.
- Full loading of plant.
- Reducing power loads.

(c) Using the heat over again, by

Multiple Effect Evaporation.

Using vapour produced by evaporation to heat process water, process liquors, air, canteen or lavatory water, central heating water, boiler feed water.

(d) Making use of any pressure drop in steam

This can be done by replacing reducing valves by an engine or turbine that will generate power when taking steam at a high pressure and exhausting to the process main at a lower pressure, or by a steam accumulator, or by an evaporator, which can evaporate process liquor or provide distilled water for either boiler feed or processes that call for very pure water. Steam at higher pressures heats the evaporator, and the evaporated vapour supplies the lower pressure process main.

An example of steam saving technique

The following account illustrates the application of the principles outlined in this chapter. Fig. 2 shows the steam and water lay-out of an imaginary factory of a very ordinary type. We need not consider what it manufactures; all that concerns us are its steam, condensate and water heating arrangements, which are similar to those of thousands of other factories.

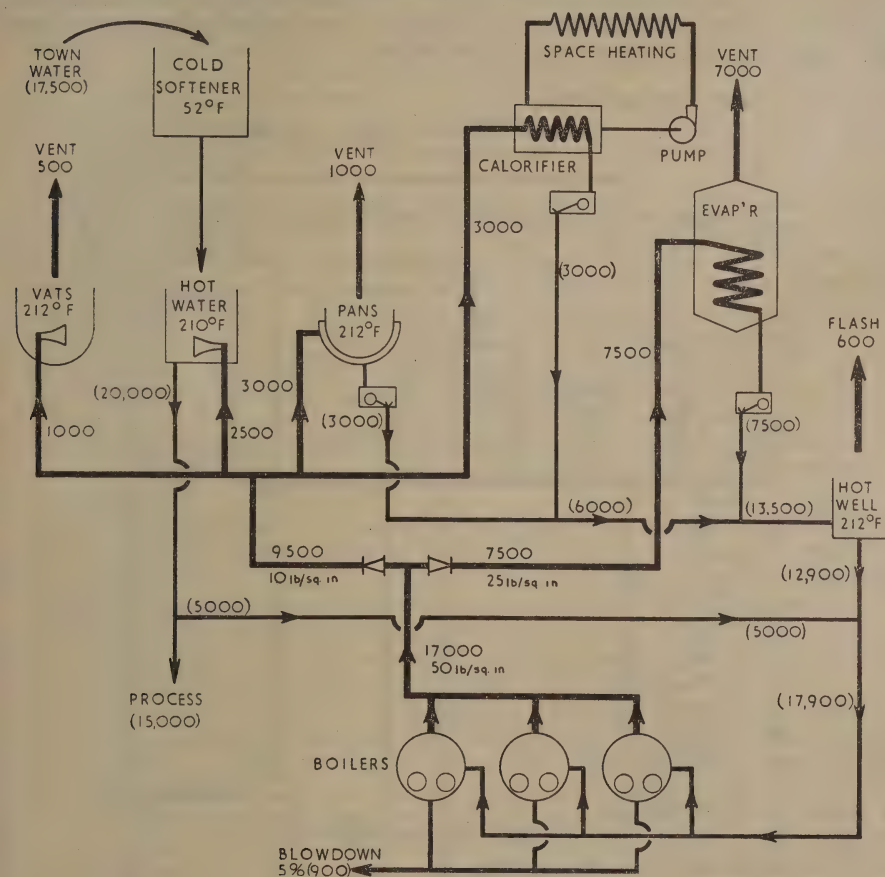


FIG. 2. Steam and water supply system in factory. (Capable of improvement.)

Three Lancashire boilers provide 17,000 lb. of steam per hour. The largest consumer is the evaporator operating at atmospheric pressure, its heating coils taking steam at 25 lb./sq. in. through a reducing valve.

An extensive space heating system calls for 3,000 lb./hr. *via* a calorifier.

The process requires 1,500 gallons of water per hour at just below boiling-point, provided by open steam blowers in the hot water tank. The remaining process plant comprises pans and vats taking, in all, 4,000 lb. of steam per hour. The calorifier, pans and vats are supplied with steam at 10 lb./sq. in. through a reducing valve.

The vapour from the pans and vats, amounting to 1,500 lb. of steam per hour, escapes through open vents to atmosphere. The condensate from the pans, calorifier and evaporator goes to the hot well where the flash of about 600 lb./hr. escapes. As the recovered condensate provides barely three-quarters

of the boiler feed requirement, make-up of about 500 gallons per hour has to be provided.

Let us see what can be done to improve the economy of this factory.

Although built for steam at 50 lb./sq. in., the evaporator works at 25 lb./sq. in. In Fig. 3 its coils are shown as taking steam at 50 lb./sq. in., the liquor being made to boil under a pressure of 10 lb./sq. in. The temperature drop under the new conditions between 50 lb./sq. in. and 10 lb./sq. in. is 298 *minus* 239, i.e. 59° F., compared with the old conditions of 267 *minus* 212, i.e. 55° F., so the evaporator performance will be improved.

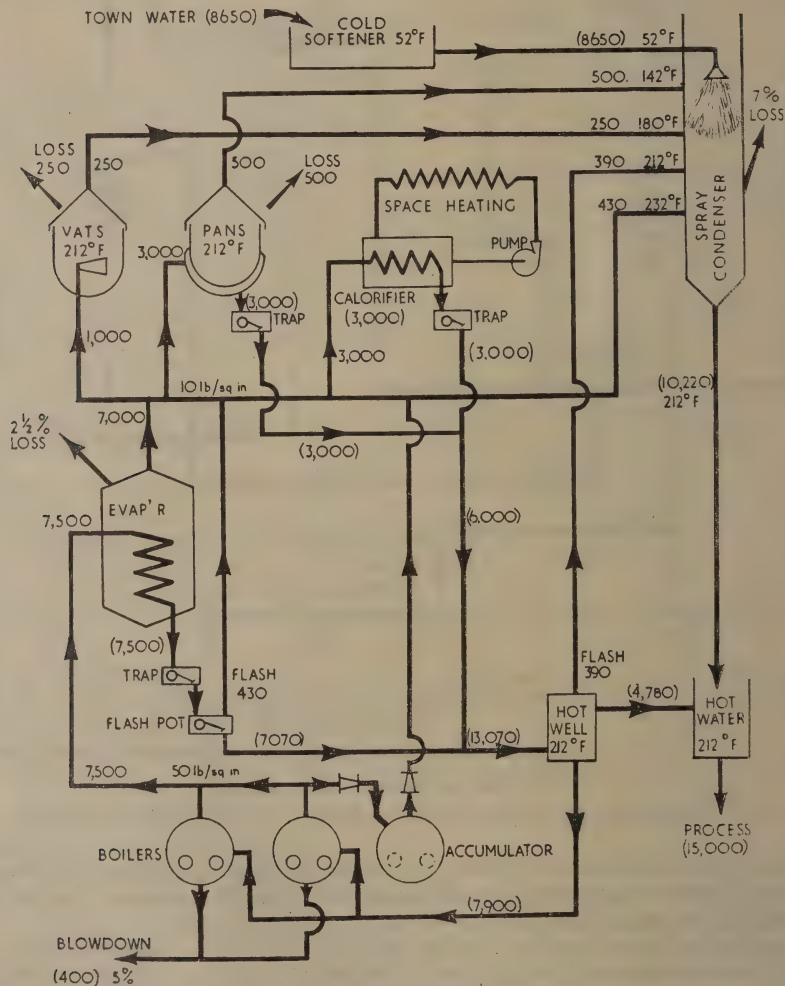


FIG. 3. Improved steam and water supply arrangements in factory to which Fig. 2 refers.

The 10 lb./sq. in. vapour from the evaporator is sufficient to supply the pans, vats, and calorifier. The condensate from the evaporator heating surface goes into a flash pot connected to the 10 lb./sq. in. main. All the condensate goes into a closed hot well, from which flash steam is piped into a long narrow spray condenser down which the cold softened town water is sprayed. This

condenser also receives the excess 10 lb./sq. in. steam. Hoods are fitted over the pans and vats and it is assumed that half the vapour can be collected from them and ducted to the spray condenser. As the boiler steam output is now only 7,500 lb. per hour, instead of the former 17,000 lb. per hour, and the amount of condensate is only slightly less, there is now a large surplus of distilled water which can help to provide the process hot water.

The various vapours supplied to the condenser are more than enough to heat the process water to boiling-point. There is, however, one most important point; the hoods over the vats cannot be tight, because inspection holes must be provided. It is assumed that there will be 50 per cent. of air in this vapour, so the partial pressure of the steam in this vapour will be half an atmosphere, i.e. 7.5 lb./sq. in. abs., and its temperature will be 180° F. Similarly, the hoods collecting the pan vapour must be movable, and provided with inspection holes. So it is assumed that this vapour will consist of four-fifths air and one-fifth steam, which gives the steam a partial pressure of one-fifth of an atmosphere, i.e. 3 lb./sq. in. abs., with a temperature of 142° F. By arranging for the coolest vapour to meet the coldest water, all the low temperature vapour heat can be used. If the ducts were led into the condenser in the opposite order, so that the pan vapour went in at the bottom, none of the heat in the pan vapour could be used because the water would have already been heated to 176° F. and could not condense vapour at 142° F.; 176° F. would be the highest temperature to which the water could be heated.

In Fig. 3 a heat loss of $2\frac{1}{2}$ per cent. has been allowed for the evaporator, and a loss of 7 per cent. of heat for the vapour ducts and spray condenser.

A small fan is fitted to the top of the condenser to remove the air and induce a mild draught.

As the load could now be carried by one boiler instead of three, two boilers are in use. This enables peaks to be met readily, and allows the boilers to work very efficiently on about half load, with such easy firing conditions that the firemen can concentrate on efficient combustion. The third boiler is converted into a type of accumulator working between the 50 lb./sq. in. boiler main and the 10 lb./sq. in. process main. This should deal with a peak variation of 7,000 lb. per hour, i.e. 100 per cent. over- or under-load.

It will be seen that these very simple alterations have cut down the steam and water consumption by more than half. It may be objected that there is only a remote chance of finding an evaporator working at half its rated pressure. To meet such an objection, let us suppose that all the units of the process plant, evaporator, vats, pans, calorifiers, to be working at 50 lb./sq. in.—a not unlikely state of affairs. By reducing the steam pressure on the essentially low pressure plant, we can still adopt the exact arrangement shown in Fig. 3, and secure the same substantial saving. The example just given is typical of what the steam technician must look for. In some cases (for example, where the vapour from the evaporator is contaminated) such a simple and spectacular arrangement might be unattainable. But there are hundreds of factories where, by doing a little juggling with the plant, it is not at all unlikely or impossible to halve the steam consumption.

PRESSURE HOT WATER

There are some heating problems for which ordinary steam technique does not provide a very good solution—for example, where the amount of heat required is very small and the steam space large, with no definite path, such as the platens of moulding presses. The heating of very long heating pipes in oil tanks ashore and at sea by means of steam is also often unsatisfactory. Circulation of steam sometimes effects an improvement, but it is often a

doubtful expedient to adopt. By circulating very hot water a precise calculable heating effect can be obtained. Water under pressure can be raised to a high temperature before it boils. Such water can be pumped round a heating system, and a temperature can be obtained at the most distant point in a manner that may be impossible using steam. The pressure must be such that there is no chance of the water boiling and forming steam pockets which, on condensing, could cause water hammer. For example, if it is desired to circulate water at 300° F., a pressure of 60 lb./sq. in. *g.* would not give a sufficient margin. Water at 60 lb./sq. in. *g.* boils at 307° F. It would be unwise to use a pressure lower than 120 lb./sq. in. *g.*, at which pressure the water does not boil until 350° F.

Pressure hot water suffers from the disadvantage that its use must be accompanied by a fall in temperature, so that if an operation calls for close temperature control the amount of water circulated must be very large in order to keep the water temperature drop small. In the "boiler" the *pressure* is no measure of the temperature, and the firing must be controlled by *temperature*. On the other hand, boilers for pressure hot water do not need the steam drums that are fitted to steam boilers. One steam drum on a range of boilers may be sufficient to cover the risk of accidental boiling of the water and to provide an expansion cushion. An existing steam plant can in many instances be converted to pressure hot water operation, much of the existing equipment being incorporated. Pressure hot water systems have the great advantage that they do not rely upon convection and do not require a falling condensate return pipe; consequently the water can be pumped in any direction, up or down.

Traps are not required. Two large pipes are needed instead of one larger steam pipe and one small condensate pipe. In theory, there is no need for any boiler feed, with its attendant feed water with its necessary treatment. In practice, however, boiler feed for which inadequate provision has often been made, is sometimes a major problem because of the loss of water caused by the draining of parts of the system for valve maintenance or by water being drawn off for illicit purposes. Furthermore, the system is virtually de-aerated, thus reducing corrosion problems and eliminating air locking.

There may be a big future for pressure hot water, but owing to the small number of installations at present operating, the experience gained probably does not warrant drawing any definite conclusions. The system may be said to suffer from the inherent disadvantage that there is no easy practical manner of using any surplus heat out of the flue gases as, for example, by the use of an economiser.

STEAM PEAKS AND THERMAL STORAGE

Wide fluctuations in the demand for steam in a factory militate against efficient boiler house operation, increase all the thermal losses inevitable in steam raising, cause variations in pressure in the steam system and lead to slowing down of processing with consequent damage to the product. Another serious consequence of fluctuating demands is the danger of priming in the boilers, due to sudden drop in pressure; this in turn leads to higher moisture content of the steam and condensation in the mains. The cumulative effect of these factors is a serious increase in the amount of fuel used per unit (e.g. ton) of product.

Maximum efficiency in boiler operation can be obtained only under a reasonably steady load, when proper attention can be paid to efficient firing and combustion control; a widely fluctuating demand for steam makes this impossible.

When a peak in the demand for steam occurs the drop in steam pressure is always greater at the consumer's end of the supply main than at the boiler end, an effect that is aggravated by the fact that steam supply mains frequently cannot cope with peak demands for which they were not designed, more especially where (as is so often the case) extensions to plant are made without regard to the steam-carrying capacity of the existing pipework.

Inadequate steam or hot water supply in processing may not only slow down the operations but also give an inferior product. The former effect leads directly to a lower rate of output and increased fuel/product ratio; the latter entails either wastage or re-processing of damaged product: the end result is the same.

The effects of steam peaks on rate of output and quality of product are innumerable. Examples could be cited from the brewing industry (sterilization of beer,) dyeworks (accurate control of colour development), coal winding (number of winds per hour), milk processing (restriction of acid content), rubber manufacture ("spotting" of rubber)³.

THE AVOIDANCE OF PEAKS AND VALLEYS

A valuable aid in the boilerhouse is a steam flow indicator which, by providing the staff with timely warning, may enable steps to be taken to meet the peak. A critical pressure gauge (see Chap. 27) may also help towards the same end. Where practicable staggering of operations in a factory can also make a valuable contribution to a solution of the problem: but few industrial processes can "clock off and on" with precision. Everything possible should be done to prevent all the steam consumers in a factory from starting up together. The familiar scramble for steam first thing in the morning or after a week-end shut-down must be prevented if serious loss of output is to be avoided. But sudden heavy demands cannot always be anticipated or accurately programmed. Some other remedy is required.

Automatic combustion control provides a partial solution of the problem—only partial, however, because peak demands are generally above the overload capacity of the boiler plant. Most boiler plant can cope with a 25 per cent. overload and both mechanical stoker capacity and draught are normally sufficient to meet this, but there is always a time lag in the response to a change in firing rate. The ultimate remedy must, therefore, be some sort of thermal storage.

THERMAL STORAGE

The principle of thermal storage can be applied in one or more of several ways. In the *Live Steam Accumulator* surplus steam is stored in water under a gradually rising pressure, and regenerated as steam under a falling pressure. In the *Feed Water Accumulator* the temperature of boiler feed water can be "topped up" by surplus steam not required elsewhere in the plant. Peak-carrying capacity of this method is, of course, limited in comparison with the *Live Steam Accumulator*.

In the *Exhaust Steam Storage System* the exhaust steam from (say) a colliery winding engine or a rolling mill engine is stored intermittently, and regenerated at a more or less steady rate to meet the needs of a mixed-pressure turbine, thus levelling out the peaks and valleys between the main consumer and the power house.

The maximum demand that a *Live Steam Accumulator* can cope with is determined only by the maximum permissible rate of steam release from the free water surface, which is high; technically, therefore, it offers a complete solution to the problem. The *Hot Process Water Storage* system, although

of more limited application, is simple and cheap. A combination of the two, where practicable, is perhaps the most satisfactory arrangement, the hot water storage system taking care of the major part of the out-of-balance heat demand and the live steam accumulator looking after the shorter, sharper (more severe) parts of the peak.

A recent development which can be of great assistance in meeting a fluctuating steam demand is the *Thermal Storage Boiler*, in which provision is made for meeting steam peaks and valleys by substantial and controlled rise and fall of water level. The shell is made considerably larger in diameter than in the normal boiler for a given amount of heating surface, and the boiler is designed for a pressure higher than is required in the factory, the process pressure being held constant by a reducing valve. This adds to the thermal storage effect of the boiler. Guidance is given to the stoker by a master firing gauge which indicates the need for increasing or decreasing the rate of firing.

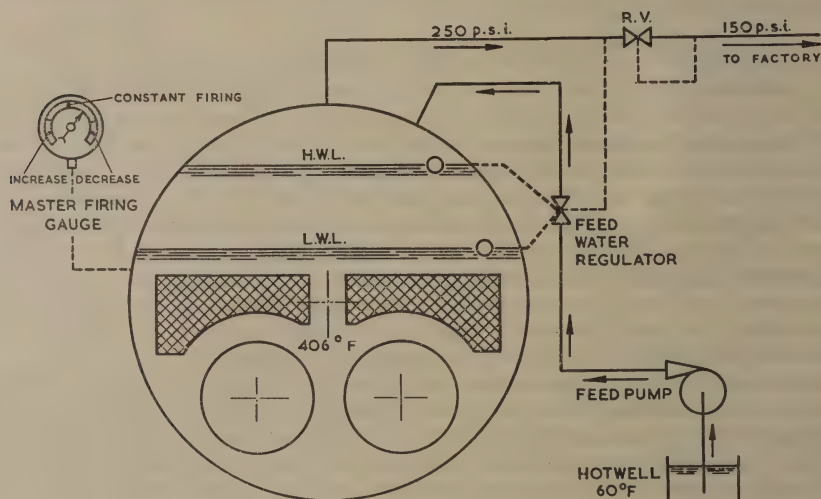


FIG. 4. Thermal storage boiler (Economic type)

Figure 4 is a diagrammatic representation of a Thermal Storage Boiler recently installed in a factory in Britain⁴.

REFERENCES.

- ¹ LYLE, Sir OLIVER, "The Efficient Use of Steam", 1947, London, H.M.S.O.
- ² NORTHCROFT, L. G., "Steam Trapping and Air Venting", London, Hutchinson. Scientific and Technical Publications.
- ³ RITCHIE, E. G., *J. Inst. Fuel*, Dec., 1948. "Steam Peaks".
- ⁴ "The Thermal Storage Boiler", *Steam Engineer*, Dec., 1956, 82.

CHAPTER 18

GAS PRODUCERS

GENERAL

PRODUCER GAS is made by blowing air and steam through a bed of incandescent solid fuel under such conditions that the combustible matter of the fuel is converted into combustible gases. Gas obtained in this way finds application in many industrial processes.

The account of the principles of gasification given in Chapter 6 indicates that in the simplest case, in which dry air is blown through a bed of coke of sufficient depth and at a sufficiently high temperature, the gas obtained consists almost exclusively of carbon monoxide and nitrogen in the ratio of about 1:2 by volume, with only traces of carbon dioxide and hydrogen. If coal is used under similar conditions, the gas contains additional hydrogen and methane derived from the volatile matter of the coal. In the earliest producers, of about a century ago, such conditions were used and gave gases of the following compositions and calorific values:

Fuel used	Composition of gas made (per cent.)						Calorific Value* B.t.u./ft ³
	CO ₂	O ₂	CO	H ₂	CH ₄	N ₂	
Coke ..	1.5	—	32.5	1.0	—	65.0	106
Coal ..	1.0	—	31.0	5.0	2.0	61.0	134

* gross, sat'd. at 60° F. and 30 in. mercury.

Such conditions, however, do not provide the maximum thermal efficiency or the most satisfactory operating conditions, because the heat liberated in the combustion of carbon to carbon monoxide is much greater than would be sufficient to maintain a suitable temperature in the bed of fuel. Consequently the fuel bed temperature becomes excessively high and much of the potential heat of the fuel leaves the producer as sensible heat in the gas. Another undesirable consequence of the high temperature is the fusion of the ash, with the formation of clinker.

The addition of steam to the blast was introduced later to increase the thermal efficiency and moderate the temperature of the fuel bed by generating additional combustible gas by the reaction of steam with carbon,

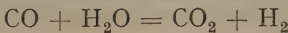


which takes place with absorption of heat. Typical gas compositions obtained in this way are:

Fuel used	Composition of gas made (per cent.)						Calorific Value* B.t.u./ft ³
	CO ₂	O ₂	CO	H ₂	CH ₄	N ₂	
Coke ..	6.0	—	27.0	12.5	0.6	53.9	132
Coal ..	6.0	—	26.0	15.0	2.5	50.5	156

* gross, sat'd. at 60° F. and 30 in. mercury.

It will be observed that these gases contain appreciable proportions of carbon dioxide. This does not necessarily imply that any carbon has been burnt without contributing to the thermal value of the gas made: it is due to the "water-gas shift" reaction



in which some of the steam reacts with carbon monoxide. Since for each volume of carbon monoxide converted to carbon dioxide in this way an equal volume of hydrogen (of approximately the same calorific value as carbon monoxide) is added to the gas, no nett loss is involved.

Gas producers are of several different types, depending on the purpose for which the gas is required. The choice of fuel, also, depends on the use which is to be made of the gas. The principal fields of utilization of producer gas, with the type of gas required in each case and the type of fuel which satisfies the special requirements of each field, are shown below.

<i>Application</i>	<i>Type of gas required</i>	<i>Fuel</i>
Heating coke ovens	Cold, clean gas	Coke
Regenerative furnaces (steel, glass)	Hot gas of maximum C.V.	Bituminous coal
Heating gasworks retorts (horizontal or vertical)	Hot gas (built-in producers) Hot, partly clean gas (separate producers)	Coke Coke
Dilution of coal gas	Cold, clean gas	Coke
Stationary gas engines	Cold, clean gas	Coke, anthracite, charcoal, wood etc.
Vehicle producers	Cold, clean gas	Anthracite, charcoal, wood, coke

Where the heating value of the gas is the main consideration, the producer may be built into the furnace or retort setting, or the gas may be distributed hot through insulated mains to furnaces close by, to avoid loss of sensible heat. Coal is preferred to coke or anthracite for some operations because the hot gas from coal contains tarry vapours; these increase both its calorific value and the proportion of radiant heat emitted during combustion.

Where the gas must be distributed over greater distances, or where its freedom from dust, tar, condensable vapours and in some cases sulphur compounds is important, it must be cooled and cleaned before distribution. For such purposes coke and anthracite are the simplest fuels to use, but with adequate gas cleaning plant bituminous coal can also be used.

The commonest types of gas producer are vertical cylindrical chambers into which fuel is fed continuously from the top. Air is blown through a grate at the base, and the gas exit is at the top. Ash and clinker are discharged at the grate. The chamber may be lined with firebrick or may have an annular water jacket in which steam is raised for addition to the blast.

Fig. 1 is a diagrammatic sketch of such a gas producer, and Fig. 2 is a more detailed diagram of a plant for making cold clean gas from coke. Fig. 3 shows the more elaborate plant required to make cold clean gas from coal.

THE FUEL BED

The fuel bed can be thought of as divided into a succession of horizontal zones as shown in Fig. 1, corresponding to successive stages in

- (i) the removal of carbonaceous matter from the fuel as it travels down the bed, starting as fresh fuel at the top and ending as ash at the base,
- (ii) the changes in composition of the gases rising through the bed, starting as a mixture of air and steam at the base and ending as producer gas at the top.

These zones are usually described as follows:

(a) *The ash zone*, extending upwards from the grate to the level at which the descending fuel still contains burning carbon. The thickness of this zone can be varied at will by controlling the rate of removal of ash, and must be sufficient to prevent overheating of the grate by the fire. When the ash is of a suitable texture it assists in the uniform distribution of the air blast over the cross-section of the fuel bed, and the hot ash leaving the fire zone above it pre-heats

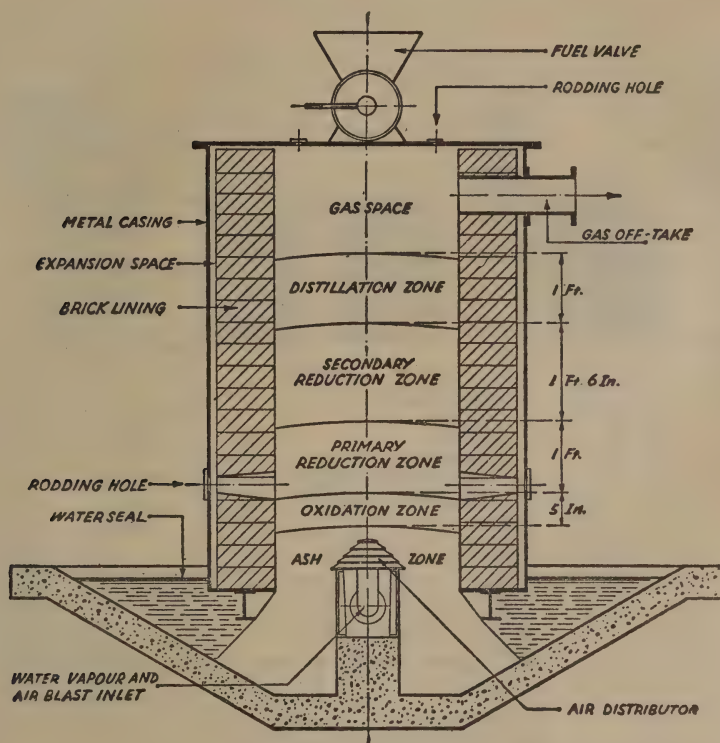


FIG. 1. Diagrammatic sketch of a gas producer.

(Reproduced by permission from "Producer Gas Plant for Industrial Purposes," published by The National Federation of Gas Coke Associations, The British Hard Coke Association, and The South Wales Anthracite and Dry Coal Committee.)

the air to some extent, and minimises loss of sensible heat in the ash which is discharged.

(b) *The combustion (or oxidation) zone*, in which the oxygen in the air blast reacts with the carbon in the fuel. The oxygen in the blast is completely consumed after passage through a relatively thin layer of fuel, commonly 4–6 inches thick (more specifically, 3 to 5 times the average particle diameter of the fuel). Gas samples taken from this zone show that the main product of combustion is carbon dioxide, with some carbon monoxide towards the top of the zone*. In consequence of the high heat of combustion of carbon to carbon dioxide, the temperature reached by the fuel in this zone is the highest in the fuel bed; with a dry blast it may reach $1,600^{\circ}\text{C.}$, but with a humidified blast it is moderated by the simultaneous reaction of steam with carbon (which absorbs heat), and by the additional heat capacity of the blast. In normal practice, the proportion of steam in the blast is so regulated that this temperature is only sufficient to cause slight sintering of the ash, giving it a granular texture which facilitates its discharge at the grate, and avoiding the formation of massive lumps of clinker.

* It is probable that carbon monoxide is, strictly speaking, the primary product of the combustion of carbon with oxygen; but while free oxygen is still present in the gas surrounding the particles of fuel this carbon monoxide burns to carbon dioxide immediately it is formed.

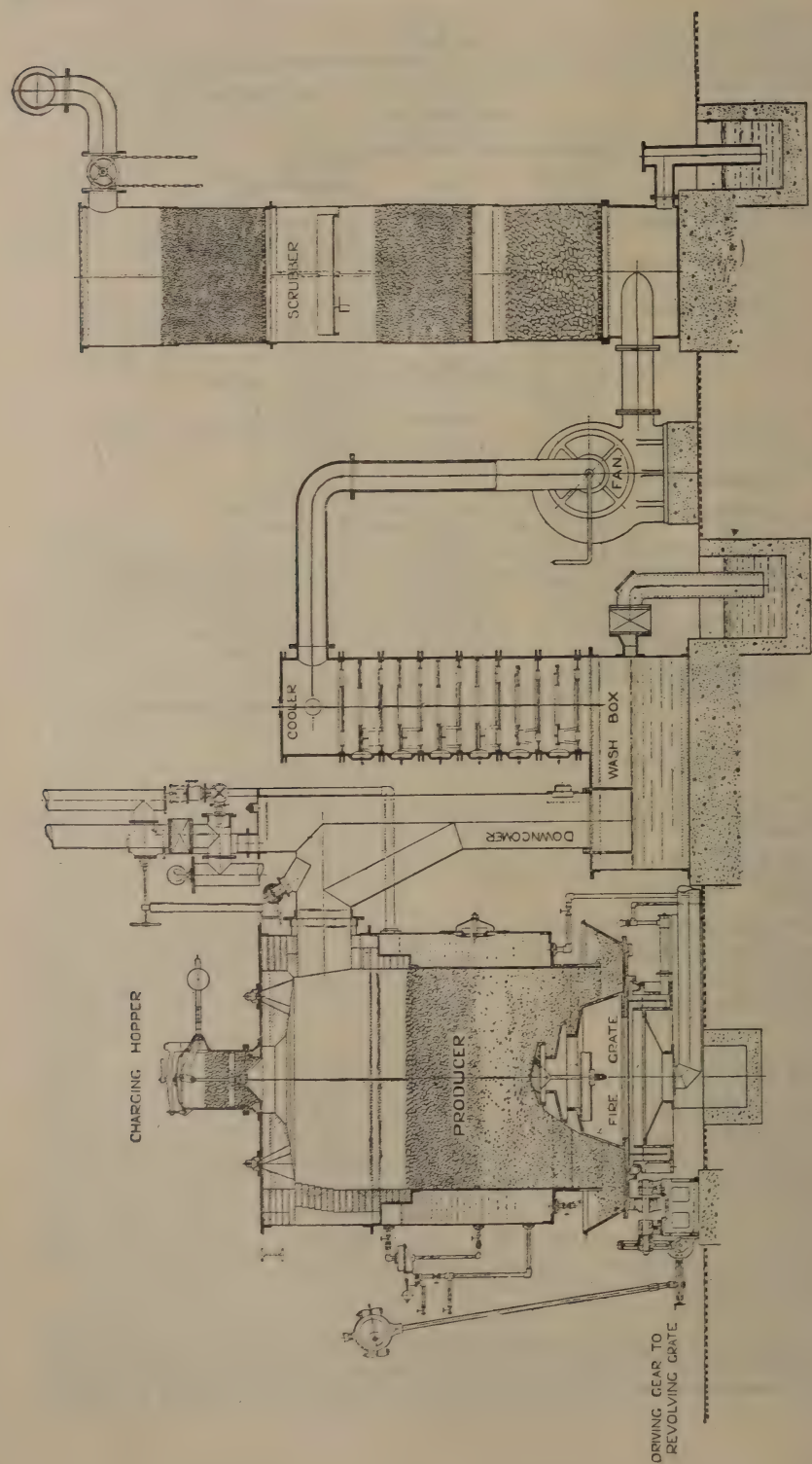


FIG. 2. Diagram of plant for making cold clean producer gas from coke.
(Reproduced by permission from "Producers Gas Plant for Industrial Purposes," published by The National Federation of Gas Coke Associations, The British Hard Coke Association, and the South Wales Anthracite and Dry Coal Committee.)

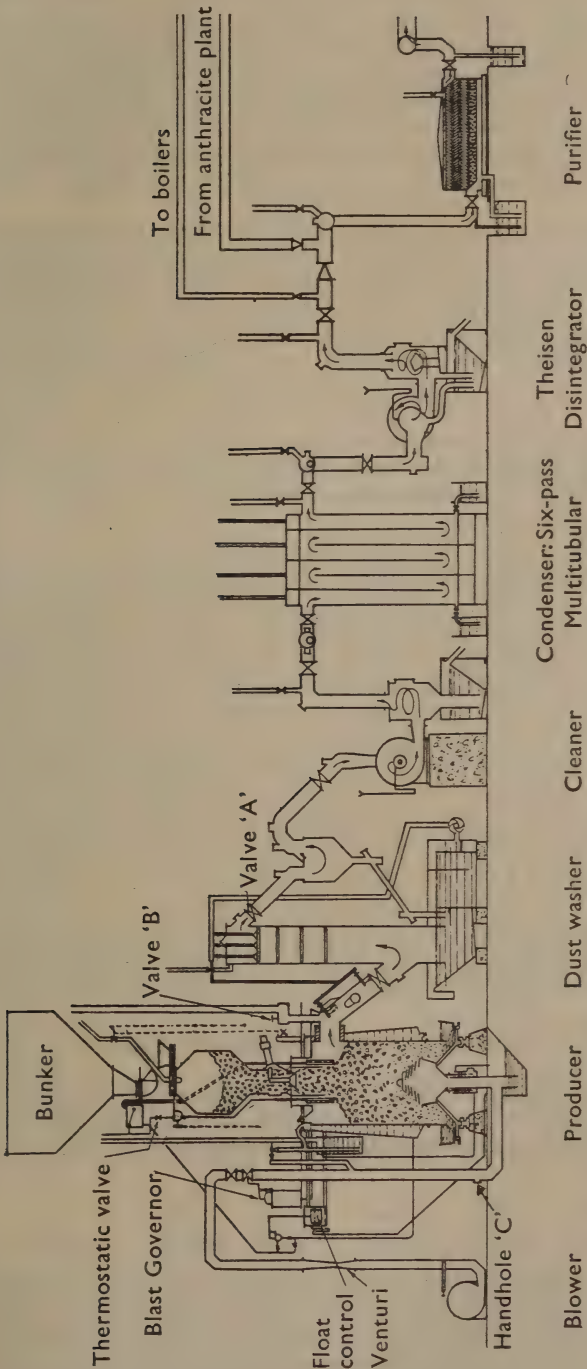


FIG. 3. Diagram of plant for making cold clean producer gas from bituminous coal.
(By courtesy of The Power Gas Corporation Ltd.)

(c) *The reduction zone.* This extends from the level at which no significant amount of free oxygen remains in the gas up to that at which no further reaction of *fixed* carbon with carbon dioxide and steam occurs. The gas entering this zone from below has a high content of carbon dioxide and water vapour and is at a high temperature. At the temperature of $1,100^{\circ}$ – $1,200^{\circ}$ C. to which the fuel at the base of this zone is heated (by radiation from the combustion zone beneath it and by heat exchange with the gas), the reactions



are very rapid, so that the content of combustible gases—carbon monoxide and hydrogen—in the gas rises rapidly and the carbon dioxide and steam contents fall, as the gas passes through the reduction zone. Since these reactions absorb heat, however, the temperature falls with increasing height above the grate. This drop in temperature and the progressive disappearance of the carbon dioxide and water vapour slow down the gasification reactions until, about 20 to 30 inches above the top of the combustion zone, a level is reached at which the temperature of the fuel is between 800° and 900° C. and no significant further gasification of fixed carbon occurs by the above reactions. Apart from the effect of losses of heat to the walls, the bed temperature remains constant above this point up to the zone in which heating and carbonization of freshly-charged fuel are still in progress.

(d) *The distillation zone.* Fresh fuel fed to the top of the bed comes into contact with fuel that has already become heated and with the hot gases leaving the reduction zone. It is successively dried, pre-heated, and (if the fuel is coal) carbonized, adding water vapour, tarry vapours, and carbonization gases to the gas leaving the producer. A certain amount of cracking of tar and reaction of hydrocarbons with undecomposed steam takes place. The character of the products added to the gas from the volatile matter depends on the type of fuel used; cokes give only traces of tar and hydrogen, anthracite gives a good deal of hydrogen and methane with little tar, bituminous coals give large quantities of tar and gases. The fuel-bed zones are not, of course, sharply separated, since successive zones merge into each other.

It will be appreciated that the successful operation of gas producers depends on the maintenance of a fuel bed of uniform permeability to gas, in which the above zones are distributed uniformly and horizontally across the gasification chamber and maintain their correct depths. Failure to maintain such conditions results in “channeling”, “hot spots”, “marginal burning” and the like, with lowered thermal efficiency, difficulty of operation, and inferior gas quality.

COMPOSITION OF PRODUCER GAS

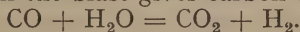
The major constituents of producer gas made with coal and coke have already been indicated in the analyses quoted. Producer gas made from either coal or coke, however, under normal operating conditions, has a composition within the range

CO ₂	CO	H ₂	CH ₄	N ₂
3–9	20–30	11–20	0–3	46–55 per cent.

In addition to the above permanent gases, a considerable number of minor constituents must be considered. These are undecomposed steam, tarry vapours, dust, sulphur compounds, ammonia, and traces of cyanogen, nitrogen oxides, and volatile mineral constituents of the ash. Of these, only the tar and ammonia are of value, and even so only in certain cases. The significance of these minor constituents is as follows:

Undecomposed steam

This includes the moisture in the fuel, water formed by distillation of coal, and that part of the steam added to the blast which has passed through the fuel bed without reacting. Water vapour is an undesirable constituent of producer gas since it increases the volume and heat capacity of the hot gas uselessly. If the gas is not cooled, a large volume of water vapour passes with it into the furnace, lowering the flame temperature if the gas is used hot. Also, undecomposed steam from the blast gives carbon dioxide by the reaction



This reaction is commonly known as the Water Gas Shift Reaction. Although this does not reduce the thermal output of gas, it lowers the calorific value of the cold gas and increases its heat capacity. It is rarely possible, however, to reduce the carbon dioxide content of the gas below about 5 per cent. by reducing the steam input, without causing overheating and clinker in the combustion zone of the producer.

Tar

When the gas is to be used in its crude hot state, it contains tar vapours. Some of the tar, however, is deposited in the gas mains, and these must be cleaned periodically, usually by burning out. It is clearly desirable to minimise deposition of tar in the mains, and this can be effected both by gasifying under conditions which give a light fluid tar which does not readily condense (i.e. avoiding excessive cracking of tar vapours) and by keeping down to a minimum the amount of dust entrained in the gas, since dust provides nuclei for the condensation of vapours. Producers have been developed, and have recently found increasing favour, in which the temperature in the distillation zone is kept low by using a deep fuel bed and withdrawing most of the gas below the distillation zone. The tar is then obtained in a very fluid form, and both gas and tar are claimed to be exceptionally free from dust; if the final gas is to be used hot, the two gas streams are mixed outside the producer and give very little deposition in the mains. These are sometimes called 'double-gas' or "pre-distillation" producers.

When cold clean gas from bituminous coal is desired, tar is removed in scrubbers.

Dust.

Dust is a major cause of fouling of gas mains carrying hot raw producer gas. Excessive dust contents may result from poor conditions in the fuel bed (blow-holes and channeling), excessive moisture in the fuel, high rates of gasification involving high exit gas velocities, or the use of fuels containing fines and dust or which disintegrate badly on heating. Some form of dust catcher is desirable even on producers making hot raw gas. In producers making cold clean gas, the cleaning plant separates both dust and tar. The maximum dust content permissible in gas intended for heating coke ovens is 0.03 grain/cu. ft. when using coke. For low-speed stationary gas engines a reasonable maximum is 0.01 grain/cu. ft.

Sulphur

For each 1 per cent. of sulphur in the fuel gasified, the gas made contains about 100 grains of sulphur per 100 cu. ft. Practically the whole of the total sulphur in most fuels finds its way into the raw gas. The greater part is contained in the gas as hydrogen sulphide, but some sulphur dioxide is also present, and may react with hydrogen sulphide, depositing solid sulphur.

Where hot raw gas is used, the only means of controlling the sulphur content of the gas is the selection of coals of low sulphur content; for example, the

sulphur content of the coal must be below 1 per cent. for acid steel melting, 1.5 per cent. for metal heating, and 2 per cent. for basic steel melting.

Where cold clean gas is made, some sulphur is removed by the washer-coolers and scrubbers. Complete removal of hydrogen sulphide can be effected by passing the gas through boxes containing iron oxide. Sulphur in producer gas, apart from being deleterious to the charge in some direct-fired furnaces, causes corrosion, particularly of waste-gas flues if temperatures low enough to allow sulphuric acid to condense. (See Chapter 11, "Gas side deposits".)

Even after purification by iron oxide, producer gas still contains a few grains of sulphur per 100 cu. ft. in the form of organic compounds.

Ammonia

When coal is gasified in producers, a large proportion of the nitrogen contained in it is converted to ammonia; this ammonia is dissolved by the wash waters when the gas is cooled and cleaned. Before the production of synthetic ammonia was developed, coal was gasified on a large scale in Mond producers with the primary object of obtaining a maximum yield of ammonia; a superheated blast and an excess of steam were used, giving a gas of the composition (per cent.)

CO_2 16.0, CO 11.0, H_2 25.0, CH_4 2.7, N_2 45.3, (C.V. 142 B.t.u./cu. ft.) in a typical case, and yielding 90 lb. of ammonium sulphate and 20 gal. of tar per ton of bituminous coal. This process was a major source of industrial ammonia abroad from about 1885 to 1920. In modern producers recovery of ammonia is of no economic importance.

Other impurities

Cyanogen compounds, unsaturated hydrocarbons, and oxides of nitrogen are found in traces in producer gas, and are liable to form deposits that may give trouble in engines.

FUEL FOR GAS PRODUCERS

The fuels commonly used are gas coke and oven coke, anthracites, dry steam coals, and non-caking or weakly-caking bituminous coals. The use of non-caking fuels ensures that the fuel bed remains uniformly permeable to the blast and to gases. Further, to facilitate the maintenance of uniform permeability of the bed to the gas it is customary to use closely-sized fuels. Any condition, such as the presence of fines, which tends to cause uneven flow of gas through the bed impairs the quality of the gas made and limits the output of the producer.

With bituminous coal a closely sized grade of size $1\frac{1}{4}$ – $\frac{3}{4}$ inch, with a minimum of fines, is preferred. With coke and anthracite, sizes as near as $\frac{3}{4}$ inch as possible are regarded as ideal for some large plants, while for others, sizes of 1–2 inches are used. Special producers are made to operate with smaller sized fuels such as anthracite grains, coke breeze, and waste products such as saw-mill refuse, but these can operate only at low rates of gasification.

Suitable coals for producer operation are obtained from all British coalfields. The National Coal Board gives the guide shown in Table 1 for the selection of coals for gas producers, in terms of the British coal types according to rank.

Producers equipped with mechanical devices for breaking up agglomerates are used with some caking and swelling coals, but even with the most elaborate of these it is not possible to use strongly caking coals.

TABLE 1

<i>Description of coal</i>	<i>Volatile matter per cent. (dry, m.m.-free)</i>	<i>Caking properties</i>	<i>Coal Rank Code No.</i>	<i>Typical B.S. Swelling Index</i>	<i>Types of producer plant for which suitable</i>
Anthracite ..	3.5- 6.0	non-caking ..	100a	1	} All types; no tar re- moval required
" "	6.1- 9.0	" "	100b	1	
Dry steam ..	9.6-11.5	" " "	201a	1	} All types
" "	11.6-13.5	" "	201b	1	
Coking steam	13.6-15.0	weakly caking	202	1½-3	Leveller bar needed
" "	15.1-17.0	medium	203	4 -5	None
" "	17.1-19.5	strongly "	204	7 -9	None
High volatile	33.1-37	medium "	601	4 -6	} Leveller bars required but coal not recom- mended
" "	>37	" "	602	4 -6	
" "	33.1-37	weakly "	701	2 -3	} Leveller bars required
" "	>37	" "	702	2 -3	
" "	33.1-37	very weakly caking	801	1½	} All types may be suitable
" "	>37	" "	802	1½	
" "	33.1-37	non-caking ..	901	1	} All types
" "	>37	"	902	1	

The characteristics of the ash of the fuel are important. A low ash content is desirable but not essential, and fuels containing more than 15 per cent. of ash can be gasified quite satisfactorily in producers equipped with mechanical grates. The ash fusion temperature, however, is of great importance. If it is low, and particularly if the ash is very heterogeneous, a high proportion of steam in the blast is required to avoid clinker troubles, as will be appreciated from the general description of the fuel bed given above. A high fusion temperature of the order of 1,400° C., therefore, allows gas of a higher calorific value to be made. It is important that attention should be paid to control of clinker formation by control of the blast saturation temperature when the fuel supply is variable or when a change is made in the source of supply. For anthracite and coke the lowest permissible ash-fusion temperature is about 1,150° C., measured under reducing conditions.

TYPES OF GAS PRODUCERS

The types of producer in general use can be classified as follows:

- (i) *Static*: Hand-fed, hand-poked, and hand-ashed.
- (ii) *Mechanical*: Mechanically fed, mechanically agitated, poked or levelled, and mechanically ashed.
- (iii) *Semi-mechanical*: in which some of these operations are carried out by hand and some mechanically.

Producers vary in size up to about 12 feet in internal diameter, and can accommodate fuel beds up to 10 feet in depth. Typical examples in the small size range were the 2- and 5-therm units used in emergency for making industrial heating gas during the 1939-45 war. The 2-therm unit was of the cross-draught type normally used for road vehicles and was only 1 foot 6 inches diameter. The 5-therm unit was of the more conventional updraught type, being 2 feet 3 inches diameter, and was lined with refractory. In the larger

units the grate is normally in the form of a "mushroom" or hood, with annular slots through which the blast is distributed as uniformly as possible over the cross-section of the fuel bed. Removal of ash may be effected by a continuously or intermittently rotating grate, for example by giving a helical contour to the rings of air nozzles so that the ash is moved radially outward and expelled by rotating or fixed ploughs. Alternatively the grate may be fixed and the shell of the producer rotated. Sometimes the grate is rotated eccentrically, providing a gentle agitation of the whole bed and crushing any masses of clinker which may form and ejecting loose ash through the slots in the grate. (See Fig. 2.)

The ash usually falls into a water-sealed annular trough, but devices for dry ash removal exist.

The shell may be lined with firebrick or may have a water-jacket in which steam is raised. Water-jackets are most common with the larger producers, and their use has the advantage that adhesion of clinker to the walls is impossible. Provided that the means used for charging the fuel maintain a uniform bed (as previously emphasized), any small amount of the blast that passes preferentially through the cool layer of fuel in contact with the wall does not cause a significant loss in gas quality.

The method of feeding the fuel is important, particularly if it is not very uniform in size. Dumping the fuel on to the centre of the top of the bed gives a conical-topped bed with the finest particles at the centre and the largest lumps round the wall. This causes the blast to pass preferentially round the margin of the bed and gives poor operation, with risk of clinkering, breaking-through of the fire, and poor quality gas. Well-designed mechanically fed producers are therefore equipped with means for ensuring that the top of the bed remains level and that no undesired segregation of sizes occurs, by the use of rotary distributors, levellers, etc. In water-jacketed producers, some preferential direction of the finer particles to the periphery is desirable, to counteract the natural tendency of the gas to flow near the wall, where temperatures are low. Mechanical distributors, levellers, and rakes are commonly water-cooled.

When caking coals are used, rotary or oscillating water-cooled mechanical pokers are often provided to break up agglomerates and maintain a uniformly permeable bed.

RATES OF GASIFICATION

Gasification rates are usually expressed as pounds of fuel per square foot of hearth area per hour, the hearth (or grate) area being taken as the cross-section of the producer. The rating may also be expressed as therms of gas an hour, especially in connection with producers making clean gas.

The nature of the fuel, its size, its ash content, and the character of the ash all affect the maximum rate of gasification which can be attained in a given producer without impairing gas quality or causing difficulty in operation. The design of the producer, and in particular the form of the grate, method of distributing the blast, and means adopted for maintaining a uniform fuel bed, are also important factors. Therefore for every producer there is a maximum economic rating for any particular fuel. Attempts to operate at higher ratings result in reduced efficiency and operating difficulties such as clinker trouble and excessively high gas-offtake temperatures.

EFFECTS OF CAKING PROPERTIES

Feebly caking, well-sized bituminous coals can be gasified in mechanical producers at about 50 lb. per sq. ft. of hearth area per hour, whereas well-sized medium-caking bituminous coals cannot be gasified at rates exceeding about 30 lb. per sq. ft. per hour, except with the most elaborate mechanical poking and breaking devices.

SIZE OF FUEL

If bituminous rough slack, say $1\frac{1}{4}$ –0 inch, is used instead of closely-graded coal sized $1\frac{1}{4}$ – $\frac{3}{4}$ inch, the economic rate of gasification is reduced by about 50 per cent.

Where a producer is designed for a particular size of fuel, the use of a smaller size reduces the capacity.

In producers used for gasifying coke breeze, it is the amount of material below $\frac{1}{8}$ in. that largely dictates the maximum rate of gasification.

METHODS OF CHARGING AND ASH REMOVAL

Mechanical producers give much higher rates of gasification than static producers. The following figures illustrate the order of differences in rates obtained with the same class of fuel:

Weakly caking bituminous coal in mechanical producer	.. 50 lb./ft ² h.
Weakly caking bituminous coal in static producer, mechanically fed and agitated but manually ashed	.. .. 20 lb./ft ² h.
Weakly caking bituminous coal in completely manual static producer	.. .. 15 lb./ft ² h.

DESIGN OF GRATE

This is receiving increasing attention from manufacturers. Changes in grate design have increased rating with anthracite from 20–30 to 50–55 lb./ft²h. over long periods.

EFFICIENCY

Figures purporting to represent the thermal efficiencies of gas producers are not always accompanied by sufficient detail of the conditions of test, or of the items included in the heat balance, and are therefore sometimes misleading. According to the British Standard method of testing gas producers (BS.995)¹, the efficiency can be expressed in the following three ways:

- Hot gas efficiency = (Total heat of gas) \div (Total heat of fuel) \times 100,
- Cold gas efficiency = (Potential heat of gas) \div (Total heat of fuel) \times 100,
- Comprehensive efficiency
= (Total heat of gas + heat in surplus steam) \div (Total heat of fuel + total heat of make-up steam + thermal equivalent of energy consumed) \times 100

In these expressions "total heat" means the sum of

- the potential heat corresponding to its calorific value, and
- the sensible heat due to any pre-heat it may have received.

All values are expressed as B.t.u. per ton of dry, but not ash-free, fuel. Each efficiency can be based on either gross or net calorific values for potential heat of fuel and gas, as desired, provided that the basis is specified and that the gross or net values are used consistently. It is necessary to distinguish between the cold clean gas efficiency and the higher value which can be obtained by including the sensible heat of tar, etc.

The following points must be borne in mind:

- The total heat of the gas at the exit from the producer shell comprises potential and sensible heats of the permanent gases (CO_2 , CO , H_2 , CH_4 , N_2), undecomposed steam (including its latent heat), tar and oil vapours and impurities, and dust.
- Part of the tar and dust are deposited in the mains between the producer and the point of application, and the temperature of the gas falls at the same time. Hence the hot-gas efficiency has a definite meaning only if it is referred to a particular point in the main.

Compared with that of other gas-making plant, the thermal efficiency of a well-designed and correctly operated gas producer is high. Cold gas efficiencies usually range between 63 and 80 per cent. Radiation and cinder losses should not exceed 9 per cent. The sensible heat in the gas at the outlet of the producer is 11–28 per cent. of the total heat input. Some 97–98 per cent. of the heat input comes from the fuel itself, the balance being from the steam in the blast.

The following figures have been quoted² for a 38-day test with a mechanical producer 9 feet internal diameter, with water-jacket, automatic gravity feed with multiple water-cooled distributor, and rotating grate for continuous ash removal. The rated capacity was 1 ton of coal per hour (35 lb./ft²h.) and the plant was operated at 56 per cent. load factor. The fuel was a high-volatile non-caking coal containing 12.7 per cent. moisture and 6.2 per cent. of ash (dry basis). The gas was cleaned in a train consisting of a dust washer (hot water), a centrifugal cleaner (hot tar), a Lymn washer (cold water), a centrifugal cleaner (cold water), and dry scrubber boxes (filtering material) to a final combined tar and dust content of 0.04 g/m³ (0.02 grain/ft³). The cold gas thermal efficiency obtained was 75 per cent.

A figure of 87 per cent. was quoted for the “cold gas and tar thermal efficiency”—a theoretical figure, as tar would not exist in cooled gas.

A similar producer making hot raw gas would give a hot-gas efficiency well above 90 per cent.

PRACTICAL OPERATION OF A PRODUCER

FUEL CHARGING

With manual operation, hopper charging is usual; mechanized units use a variety of continuous feeding mechanisms, the importance of which has already been pointed out. The hopper has a gas-tight cover and is provided with a bell or valve at its base, capable of being raised or lowered from the outside to admit the fuel to the producer. Mechanical devices to assist in the uniform distribution of the fuel must be adequately protected against damage by heat, gas, and tar.

Where the feed is discontinuous, as in manual operation, it is best to feed small quantities at short regular intervals (say 10 or 15 minutes), varying the amount of fuel according to the load on the producer but keeping the intervals constant. It is most desirable that producer operators should be forewarned of impending changes in the demand for gas, so that the rate of feed may be changed in ample time and a constant depth of bed maintained.

In mechanically fed producers, care should be taken that any distributing devices are set properly and are easily adjusted to suit a change in type of fuel. Uneven feeding leads to channeling, hot spots and clinker formation, and gas of inferior quality. Mechanical feeders should be frequently inspected to ensure that no interruption in the feed is caused by blockages, which can easily result from adventitious scraps of paper or wood or tramp iron. An undetected blockage may cause trouble which will impair operation for many hours after the blockage has been rectified. Gas tightness of seals and freedom from leaks in water-cooled devices also need constant attention.

LEVELLING AND POKING

In rotary producers the levelling of the bed may be effected by a leveller or rake. In both mechanical and static producers, oscillating pokers may be used to maintain uniform conditions in the fuel bed. These devices are especially subject to wear and need suitable maintenance.

CONDITION OF THE FUEL BED

This should be examined every hour at the poke holes provided (normally in the cover-plate of the producer), using the holes in rotation so that the whole of the fuel bed is explored systematically over a period of time. Uniformity and the depth of the ash zone and combustion zone are thus kept under review.

For this purpose, a steel rod $\frac{1}{2}$ inch in diameter is inserted into the fire from the poke hole to the top of the blast hood or "mushroom", allowed to remain for $1\frac{1}{2}$ –2 minutes in the fire, and withdrawn. The red-hot portion of the rod then shows the position of the fire zone, the cooler portion below it showing the depth of the ash bed above the top of the blast hood. The position of the top of the fuel bed is then found by inserting a dip rod from the top of the producer until it rests on the top of the bed.

The ash zone should extend at least 6 to 9 inches above the *top* of the blast hood, to avoid damage to the grate by heat. Depths greater than 12 inches, however should be avoided. The hot zone should not be more than 4 to 5 inches thick; if it is, attention should be given to general running conditions, proportion of steam in the blast, removal of hot spots, etc. Occasionally, when bed conditions are poor and large clinker has formed on the wall, a number of hot zones may be found. Such a condition needs vigorous action to break up clinker or coke masses from the top with rods, adding and levelling more fuel, and then ashing the producer.

REMOVAL OF ASH. "ASHING"

The ash removed should be kept under observation, to ensure that it is free from unburnt fuel and that massive clinker formation is being avoided. Under ideal operating conditions the ash is slightly sintered and coarsely granular. The prevention of excessive clinker formation is effected by steam control, always provided that the general condition of the bed is satisfactory. The sudden appearance of massive clinker and deterioration of gas quality may be due to the development of channeling, blowholes, or other discontinuities in the bed, calling for the use of the poker. Such points should be attended to before increasing the amount of steam in the blast; too much steam results in inferior gas, a "mushy" ash with a high ash-bed resistance, and reduced efficiency.

BLAST

The composition of producer gas, and therefore its combustion characteristics, depends very much on the proportion of water vapour in the blast, as well as on the type of fuel gasified. (The combustion characteristics of the gas are discussed in a later paragraph). The criterion of the proportion of water vapour in the blast is the *blast saturation temperature* (B.S.T.). Normally a regulated quantity of steam is blown into the air supply, raising its temperature to a pre-determined figure. This is called the blast saturation temperature, the air being assumed to be saturated with water vapour at this temperature. While not exactly correct, this assumption is sufficiently near the truth for practical purposes. It should be borne in mind that a further quantity of steam may enter the fuel bed as a result of the quenching of clinker in the water seal of the ashpan.

A number of studies of the extent of steam decomposition in gas producers have been made. Naturally this depends on a large number of factors (reactivity of fuel, rate of gasification, size of fuel, depth of fuel bed, temperature of fuel bed), as well as on the proportion of steam in the blast; but typically, practically the whole of the steam in the blast is decomposed when the blast saturation temperature is lower than about 55° C. As the proportion of steam

in the blast is increased the amount of steam remaining undecomposed increases, so that the thermal efficiency and the calorific value of the gas pass through a maximum and then decline. This maximum is usually in the neighbourhood of a blast saturation temperature of 60° C. The general character of the effect of blast saturation temperature on the gas composition and yield is as shown in Table 2 which refers to a producer gasifying coke.

TABLE 2
COKE-FED MECHANICAL PRODUCER SUPPLYING COLD GAS
TO CONTINUOUS VERTICAL RETORTS³

Lb. of steam per lb. of carbon gasified	0.0	0.085	0.331	0.500	0.700	0.900
Blast saturation temperature, ° C...	—	19.6	44.9	52.7	58.9	59.9
Volume of gas made per lb. of carbon (at 32° F., 29.9 in. Hg, dry) cu. ft.	89.6	89.2	86.9	87.5	89.1	96.9
Gas analysis, per cent. CO ₂ ..	2.1	2.7	4.0	5.6	7.8	10.1
(dry) CO ..	31.3	30.9	30.5	28.8	25.8	20.8
H ₂ ..	Nil	1.9	7.6	10.7	12.9	8.8
N ₂ ..	66.6	64.5	57.9	54.9	53.5	60.3
Gross C.V. (B.t.u./ft ³ at 60° F., 30 in. Hg, sat.) ..	99.5	104.2	121.2	125.7	123.2	94.3
Decomposition of steam, per cent...	—	100	100	93.5	82.3	47.3
Cold gas efficiency, per cent. ..	66.4	68.8	76.1	78.5	77.4	64.9

The optimum blast saturation temperature varies with the nature of the fuel but is usually 55–62° C. With a fusible ash, it may be necessary to use a higher B.S.T. to avoid clinker trouble, at the cost of a lower quality gas. Reactive fuels such as anthracite, high-volatile non-caking coals and low-temperature coke can be gasified satisfactorily with lower fuel-bed temperatures than gas coke and oven coke, and can, therefore, be used with higher B.S.T. (e.g. 60–62° C.).

OBSERVATIONS OF GAS TEMPERATURE

The temperature of the gas should be measured in the main and at the gas offtake of the producer. A base-metal thermocouple is suitable for the purpose, and in conjunction with a temperature recorder is a very useful instrument. For a given fuel and a fixed rate of gasification and B.S.T., the gas offtake temperature should remain constant. The gas temperature considered in conjunction with the fuel-bed zone levels shown by the rod test enables the condition of the fuel bed to be judged with considerable accuracy.

High gas off-take temperatures may indicate:

- (a) Fuel bed too thin or feed erratic or uneven.
- (b) Holes or channels in the fuel bed with local hot spots. Producer gas burning at top of bed.
- (c) Ash zone too thin or uneven. Clinker on sidewalls decreasing the effective cross-sectional area with consequent high gasification rates per sq. ft. of effective area. Clinker on blast hood, or worn or blocked blast distribution ports resulting in uneven distribution of the blast.
- (d) Gasification rates higher than normal for the producer and fuel in question.
- (e) Blast saturation temperature too low.

Low gas off-take temperature may indicate:

- (a) Fuel bed too thick.
- (b) Fuel unusually wet.
- (c) Gasification rates lower than normal for the producer and fuel in question.
- (d) Blast saturation temperature too high.

In practice, gas off-take temperatures corresponding to satisfactory operation vary considerably with the design of the producer (e.g. whether it is brick-lined or water-jacketed), the depth of the fuel bed, and the type of fuel used. The correct figure for a given producer and a given fuel needs to be decided by experience and the recommendations of the makers. Usually a good quality gas is being made when the surface of the bed is cherry-red in colour and the gas off-take temperature is about 600°C . In cold clean gas producers with water jackets, thick fuel beds are commonly used and the gas off-take temperature is below 400°C ., and the surface of the bed is black. Brick-lined producers making hot raw gas, on the other hand, may work with gas off-take temperatures of around 700°C ., but the temperature should not exceed 750°C .

Other things being equal, an unreactive fuel such as oven coke will give a higher off-take temperature than a reactive fuel such as anthracite or non-caking coal. A fuel of high moisture and volatile-matter content naturally gives a lower off-take temperature than one of low moisture and volatiles content under similar operating conditions.

GAS QUALITY

The best method of checking gas quality is by analysis. A continuous gas sample taken over a period of hours is preferable to a snap sample. Sampling of gases is dealt with in Chapter 29. For methods of carrying out a complete analysis of the gas standard text books should be consulted, but the CO_2 , O_2 and CO contents determined with an Orsat apparatus are a reliable guide for many purposes. (See Chap. 30.) Continuously recording automatic gas calorimeters are available, but require a very clean gas for satisfactory performance.

The interpretation of gas analyses will be apparent from earlier sections of this chapter.

With the aid of considerable experience, some idea of the quality of the gas can be obtained from its appearance as it leaves the poking holes above the fuel bed, particularly in the case of producers using bituminous coal. If the gas ignites at the hole, or appears smoky, the bed may be too shallow or channeling may be present. If the gas appears "dull and wet", the blast saturation temperature may be too high. A more reliable guide, however, is a properly designed test burner on the gas main, used in conjunction with gas analyses.

INSTRUMENTATION

Essential instruments include those for measuring the temperature of the blast and of the gas at the off-take. Maintenance of the pressure of the gas at a satisfactory and steady value requires either automatic control of the air supply or a readily visible pressure gauge. The installation of modern instruments is a powerful aid to efficiency of operation; coal, air, gas and steam can all be readily and effectively metered.

The most desirable instruments are:

- (a) Blast saturation temperature recorder.
- (b) Exit gas temperature recorder.
- (c) Blast pressure indicator.
- (d) Gas pressure indicator and controller.
- (e) Steam pressure gauge (on plants blown by live steam).
- (f) Air flow indicator (on plants blown by electric fans).

On producers provided with gas-cleaning equipment, four pressure gauges of the ordinary water U-tube type are suggested, in the following positions: (i) Washer-cooler inlet, (ii) Washer-cooler outlet, (iii) Dry scrubber outlet, (iv) Fan outlet. (See Chap. 27.)

LIGHTING-UP AND CLOSING-DOWN PLANT

For lighting up it is usual to build a fire of kindling material such as shavings and timber, on a bed of suitable ash. The kindling may then be set alight, or alternatively a layer of 1 foot of fuel may be placed on the top first and the shavings then lighted. When the bed is alight, fuel is fed gradually while the fire is blown by a gentle blast and lean gases escape at the blow-off pipe.

In large coke-fired producers the kindling material is built into a robust bed containing a full burden of coke.

Explosions during starting-up must be avoided by eliminating any possibility of mixing combustible gas and air. In simple plants fitted with a suction fan, the fan must not be started until the blow-off valve at the generator outlet is closed. Where an air blower and a fan are present, the blower is used in the initial stages of lighting, and the fan is not started until the fuel bed is at a bright red heat and the fuel level is above the side rodding holes.

When producers are started up from cold it is essential to purge gas mains and appliances to ensure that they are free from air before gas is supplied to them, testing by gas analysis at various points until the oxygen content is down to 0.5 per cent.

OVERHAUL OF PRODUCERS

All producer gas plants should be given a thorough overhaul at least once a year. The generator should be emptied and any repairs to brickwork carried out. With good operation the average life of the bricks is about three years, but every year some will require renewing. All moving parts should be inspected regularly, particular attention being paid to the feeding mechanism, which must be gas-tight. All water-cooled parts must be kept free from leaks, and the grate mechanism must be inspected for wear and local blockages. The water space of water-jacketed producers may need removal of scale from time to time.

Care should be taken in starting up to ensure that any new brickwork is dried out slowly.

PURIFICATION OF PRODUCER GAS

For coke and anthracite gas, the usual cleaning equipment (Fig. 2) consists of a washer-cooler in which the gas is cooled and freed from the greater part of its dust, and from the very small amounts of tar which it contains, by passage upwards through a tower charged with coke and sprayed with water. This may be followed by a filter box packed with wood chippings, wood wool, sisal fibre or other filtering medium, to remove the last of the dust. This box may also be charged with iron oxide to remove hydrogen sulphide. A gas-washing fan or other mechanical washer may be substituted for the filter box.

In large mechanical plants operating on coke the cooling tower is followed by one or two centrifugal disintegrators containing rotating blades, supplied with a stream of water. The disintegrator is followed by a spray separator.

The washer-cooler is generally packed with graded coke, 1-2 inches in size, over which water is sprayed at the rate of some 4,000 gallons a ton of fuel gasified. The water may be run to waste or re-circulated through a cooling pond of towers. In the latter case its acidity may have to be neutralized with lime to avoid corrosion. Loss of pressure in the washer-cooler is minimised by attention to the packing. Some precautions suggested are:

- (a) Regular examination of water sprays.
- (b) Inspection of water overflow at seal pots to ensure that no blockages are caused by sludge.
- (c) Measures to avoid freezing in cold weather.

(d) Use of just sufficient water for effective cooling and cleaning.

(e) Taking records of pressures at inlet and outlet.

The cleaning and purification of gas made from bituminous coal is a more difficult problem, and is less frequently undertaken. Producers for such a purpose usually operate with a deep fuel bed, which gives an extended distillation zone and produces a light volatile tar. A complete plant of this type is illustrated in Fig. 3, but many different designs exist. The development of producers with pre-distillation retorts has already been mentioned.

Where producer gas containing tar has to be cleaned, it is important to remove the greater part of the dust before any tar vapour is allowed to condense. This is accomplished by providing a large and well-insulated dust catcher before the cooler. The most satisfactory type of dust catcher is the cyclone separator; the use of baffles is less effective. The washer-coolers used are not packed with coke as are those used for cleaning gas made from coke or anthracite. Filter boxes are replaced in some plants by electrostatic precipitators for the removal of fine dust and tar fog.

In the majority of installations, removal of hydrogen sulphide is not considered necessary, and gas containing about 70 grains of sulphur per 100 cu. ft. is fed to the appliances. This is inevitable in furnaces using hot raw gas, but as already mentioned it is necessary to limit the sulphur content of the gas for certain purposes by the use of low-sulphur coals. In all cases where sulphur is not removed from the gas, appliances using the gas need to be fitted with flues to carry the products of combustion outside the building, or otherwise adequate ventilation must be provided. Special attention must be paid to the avoidance of corrosion.

When it is necessary to remove hydrogen sulphide, the well-established oxide purification system is used. (See Chapter 3.)

Occasionally deposits of salt derived from fuels containing it and volatilized in the producer appear at certain points in the system.

UTILIZATION OF PRODUCER GAS

Producer gas is mainly used for

- (i) Heating furnaces, coke ovens, and gas retorts.
- (ii) Operating gas engines.
- (iii) Diluting town gas.

When considering the merits of producer gas in comparison with other gaseous fuels, the following characteristics must be taken into consideration.

CALORIFIC VALUE, DENSITY, AND COMBUSTION REQUIREMENTS

Producer gas has a relatively low calorific value and a high density, so that the size of gas mains and the booster capacity required to transmit a given number of therms of producer gas over a given distance are greater than with other gases. For practical purposes, at pressures near atmospheric, the pressure required to convey gas through a main is given by Pole's formula (Chapter 10).

$$Q = 1,350 \sqrt{D^5 \Delta p / G_s L}$$

where Q = gas discharged, in cubic feet per hour, at 60° F. and 14.7 lb./sq. in. abs. pressure.

D = diameter of pipe or main in inches.

Δp = pressure difference between inlet and outlet of pipe, in inches water gauge.

G_s = specific gravity of gas (air = 1).

L = effective length of pipe in yards, 5 feet being added to the measured length for each sharp elbow or tee, and 2 feet for each 90° bend.

It can be shown, from Equation 33 (b), Chapter 10, that the flow of gas through burner orifices is given with sufficient accuracy (for most practical purposes) by the equation

$$Q = 1,660 ak\sqrt{h/G_a} \text{ in cubic feet per hour.}$$

where a = area of orifice in square inches.

k = co-efficient of discharge, normally 0.75.

h = gas pressure at orifice in inches water gauge.

G_a = specific gravity of gas (air = 1).

The number of therms of producer gas required to provide a given heating effect is greater than the number of therms of water gas, coke-oven gas, or coal gas which would be required, because of the greater volume of flue gas formed and consequently the greater loss of sensible heat in the stack gases. In other words the efficiency of utilization of producer gas is lower. This can be counteracted to a great extent by the use of regenerators which recover heat from the flue gas and use it to pre-heat the gas and combustion air.

TABLE 3
COMBUSTION DATA FOR PRODUCER GASES

Constituent	CO_2	C_nH_m	O_2	CO	H_2	CH_4	N_2
Calorific value B.t.u./cu. ft.*—							
gross	nil	~ 2,500	nil	318	320	995	nil
net	nil	~ 2,350	nil	318	270	895	nil
Specific gravity .. (air=1)	1.519	1-1.5	1.104	0.966	0.0696	0.553	0.972
Air required for com- bustion† Cu. ft. . .	nil	~ 20	-4.8	2.38	2.38	9.52	nil
Combustion products‡—							
dry	1.00	~ 20	-4.8	2.88	1.88	8.52	1.00
wet	1.00	~ 20	-4.8	2.88	2.88	10.52	1.00

*At 30° and 60° F. (sat'd).

†Cu. ft. of dry air for combustion of 1 cu.ft. of dry gas.

‡Cu. ft. of products from 1 cu. ft. of dry gas with dry air.

It will be noted that the presence of oxygen in the gas involves a negative term in combustion calculations.

The calorific value and specific gravity of producer gas, the theoretical air requirement for combustion, and the volume of waste gases formed in the combustion, can be calculated from the data in Table 3.

Example: The percentage composition of a sample of producer gas is:

CO_2	O_2	CO	H_2	CH_4	N_2
6.0	0.2	26.0	15.0	2.3	50.5

Thus, its gross calorific value is $(26.0 \times 318 + 15.0 \times 320 + 2.3 \times 995) \div 100$
i.e. 154 B.t.u./cu. ft. at 30° in. and 60° F., sat'd.,

its specific gravity (air = 1) is

$$(6.0 \times 1.519 + 0.2 \times 1.104 + 26.0 \times 0.966 + 15.0 \times 0.0696 + 2.3 \times 0.553 + 50.5 \times 0.972) \div 100$$

i.e. 0.858,

the volume of air required for combustion of 1 cubic foot is

$$(-0.2 \times 4.8 + 26.0 \times 2.38 + 15.0 \times 2.38 + 2.3 \times 9.52) \div 100$$

i.e. 1.185 cu. ft.

and the volume of the products of combustion is

$$(6.0 - 0.2 \times 4.8 + 26.0 \times 2.88 + 15.0 \times 1.88 + 2.3 \times 8.52 + 50.5) \div 100$$

i.e. 1.782 cu. ft. (dry)

$$\text{or } (6.0 - 0.2 \times 4.8 + 26.0 \times 2.88 + 15.0 \times 2.88 + 2.3 \times 10.52 + 50.5) \div 100$$

i.e. 1.978 cu. ft. (wet)

In the case of hot raw gas, the contribution of the tar vapours and the sensible heat of the gas to its effective calorific value must be taken into account, and the specific gravity is affected by the tar and undecomposed steam. The air required for combustion includes what is needed to burn the tar, and the volume of the products of combustion includes that of the undecomposed steam and the products of combustion of the tar.

COMBUSTION CHARACTERISTICS

The behaviour of gas in a burner depends on the speed of propagation of flame in mixtures of the gas with air, as well as on its calorific value and density. The most important factor affecting the flame speed is the hydrogen content, and since this is lower in producer gas than in water gas or coal gas, the flame speed is also lower. As a result of this, producer gas flames show a greater tendency to "lift" off burner ports. In most furnaces, however, combustion takes place in refractory burner jets, in close proximity to red-hot brickwork. Under these conditions no difficulties are experienced with flame stability and the proportion of hydrogen in the gas is not important. On most furnaces using producer gas no primary air is needed.

When producer gas is used in free-flame burners, the burner ports must be large so that the linear velocity of the gas at the port does not exceed the velocity of flame propagation and cause lifting of the flame. The hydrogen content of the gas in such cases should not be below 11 per cent.

The flame temperature obtained with producer gas, and the resulting temperatures attained in combustion chambers, are low because of its low calorific value and the large volume of waste gases, unless the gas and air supplies are preheated. In practice, furnaces using producer gas (e.g. coke ovens, glass tank furnaces, steel melting and heating furnaces) are normally of the regenerative type, in which the hot products of combustion are passed through chambers filled with chequer brick before passing to the stack. The waste gases give up heat to this brickwork, and the direction of flow through the furnace is then reversed so that the hot brickwork pre-heats the combustion air, or both the air and the gas, while the products of combustion give up their heat in a second chequer-brick chamber at the other end of the furnace; the flow is reversed at suitable intervals of time. In such furnaces, temperatures up to about 1,600°C. can be obtained readily.

While a high hydrogen content is desirable in gas intended for free-flame burners, it is generally regarded as undesirable in hot raw gas for steel melting. Here a flame of high luminosity due to tar vapours is desired, and a high hydrogen content and the associated high content of water vapour in the combustion gases are found to have an adverse effect on the intensity of radiation emitted by the flame.

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CHAPTER 19

FURNACES—GENERAL PRINCIPLES

THE primary function of an industrial furnace is to make a satisfactory product; other considerations must be subordinated to this. This principle has so prevailed in the past that the study of the fuel efficiency of many furnaces has been to a great extent neglected. When cost of fuel is only a small proportion of the total manufacturing costs, there is a tendency to regard fuel saving as unimportant; only in those operations where the cost of the fuel is important in relation to the total cost, or where the availability of suitable fuel presents difficulties, is there any incentive to watch fuel economy closely.

The efficient working of industrial furnaces thus requires the consideration of many factors in addition to, and quite distinct from, fuel economy. In the many uses to which furnaces are put, conditions may be expected to vary widely. Certain principles are, however, common to all furnaces and it is to these principles that attention is primarily directed in this chapter. The fundamental principles of combustion and heat transmission discussed in earlier chapters are of prime importance in the design and operation of furnaces.

THE SELECTION OF FURNACES

In selecting a furnace, the purpose for which it is required and the probable fuel consumption are points of primary importance. Its capacity should be related closely to the probable output since one of the main causes of heat loss lies in incompletely filled furnaces.

The cost of the fuel is a continuous charge on the heating operation, usually far outweighing the capital charges. Consequently the use of mechanical aids to operation, control instruments, and means of heat recovery should not be excluded on grounds of capital costs. An apparently high capital cost spread over the life of the furnace may in the long run produce a considerable economy.

Other matters for special attention are:

- (1) *Robustness of the furnace structure.* Besides a mechanically stable framework, good quality refractories and attention to efficient laying of the bricks are essential.
- (2) *Ease of control.* All valves, damper controls and instruments should be situated in a convenient, and as far as possible central, position to give ready accessibility for control purposes. Provided that over-elaboration is avoided, automatic control is an instrument of efficiency.
- (3) *Ease of maintenance.* This implies accessibility, the use of readily replaceable parts, and means for inspection and cleaning.
- (4) *Insulation.* This must be regarded as an essential feature of almost any type of furnace.
- (5) *Provision for adequate, preferably balanced, draught.* A chimney is not necessarily the most efficient means of providing draught. Fans should be carefully rated for the duty intended. Flues, dampers and sight holes should be so arranged and constructed as to reduce the possibility of air leakage to a minimum.
- (6) *Furnace atmosphere.* It may be necessary to heat the goods in the furnace in an atmosphere having a composition that will not injure them.

The so-called *controlled atmospheres* are provided for the heating of materials in which a specific quality of surface must be preserved. In such cases the controlled atmospheres may consist of cracked ammonia,

or other gaseous mixtures prepared from town gas, or from hydrocarbon gases, the composition of which is adjusted to meet the requirements of the materials heated and of the process to which they are to be subjected. The use of these controlled atmospheres requires the application of the principle of muffle heating.

- (7) *Recovery of waste heat.* This is applied mainly by pre-heating of the air, or of the fuel where it is gaseous, or of the furnace charge.

FURNACES ATMOSPHERES

Control of the atmosphere in a furnace is a matter of great importance and may be the dominant consideration in the selection of a fuel. The scaling of steels, as distinct from surface tarnishing that is preventable by bright annealing, is of much importance in the re-heating of material before forging or rolling operations, where the temperatures used are sufficiently high to cause excessive oxidation in certain furnace atmospheres. The active gases that may be present are oxygen, carbon dioxide and steam, usually diluted with nitrogen and possibly containing reducing and sulphurous gases. The degree of scaling is determined by the temperature of treatment (which is the most important factor), the time at that temperature, and the composition of the furnace atmosphere. An instance of the relative effects of air, carbon dioxide, and steam on a mild steel at forging or rolling temperatures is shown in Fig. 1, reproduced from "Controlled Atmospheres" by Jenkins.¹

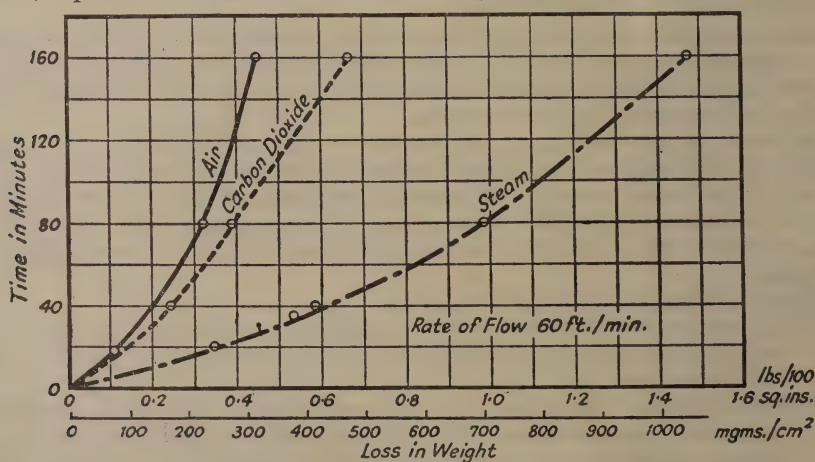


FIG. 1. Effects of air, carbon dioxide and steam in scaling of 0.19% Carbon steel (Jominy and Murphy)

FIGS. 1, 2 and 3 are reproduced by permission of Messrs. Chapman and Hall, Ltd., from "Controlled Furnaces for the Heat Treatment of Metals," by IVOR JENKINS.

Scaling is a diffusion phenomenon and is governed by diffusion laws. With specific alloying constituents in a metal, protective layers of scale may be formed; these reduce the rate of scaling. The scaling losses in oxidizing gases are substantially decreased by adding small percentages of a reducing gas, but with rising temperature higher concentrations of the reducing gas are required to effect a corresponding reduction in scaling. Thus, in a carbon dioxide atmosphere the addition of 2 per cent. of *carbon monoxide* at 930° C. will reduce the scaling losses to the same extent as the addition of 10 per cent. at 1,040° C. The addition of hydrogen to carbon dioxide will, at low concentrations, give an increase in the rate of scaling due to the formation of water vapour, which is more strongly oxidizing than is carbon dioxide.

The behaviour of water vapour and hydrogen, on the one hand, and of the oxides of carbon, on the other, in relation to the reduction of iron oxide is shown in Figs (2 and 3).

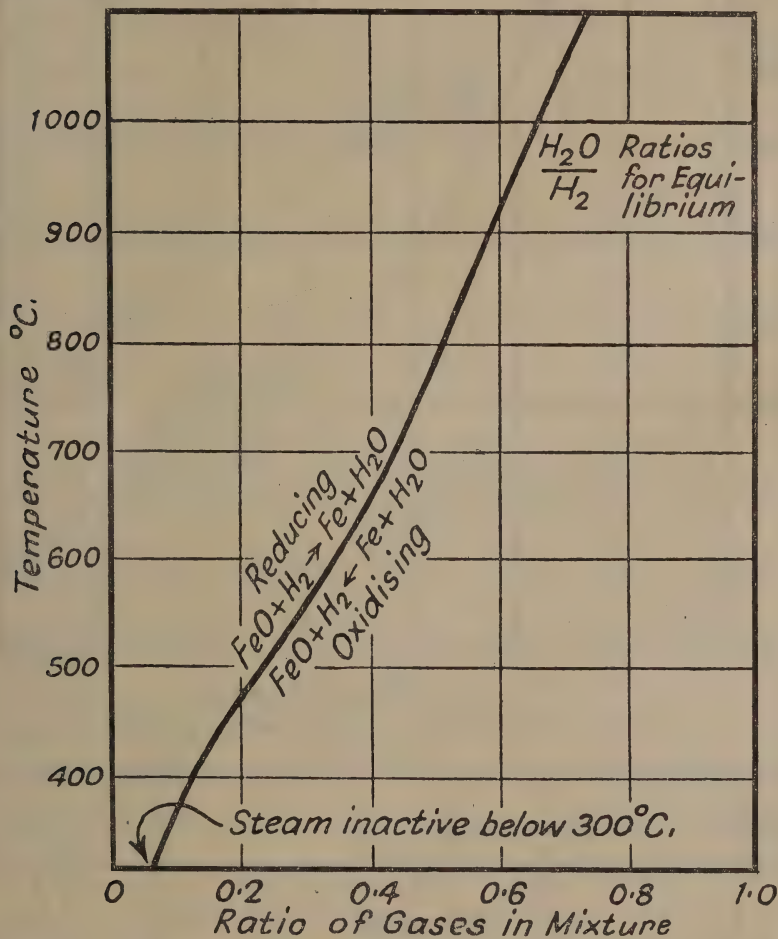


FIG. 2. Reduction of iron oxide by hydrogen.

(Chipman and Marshall)

As a practical consideration in the heating of ferrous metals the condition of the metal surface beneath the scale and the character of the scale may be more important than merely the amount of scale formed. This applies particularly to decarburization, which may follow the oxidation process and is a cause of ultimate failure of the metal in use. In producing decarburization in a combustion atmosphere moist hydrogen has by far the greatest effect, followed by carbon dioxide; air and steam are less effective.

Much of the fundamental scientific investigation on the influence of scaling gases has been done with synthetic atmospheres. (See Figs. 4, 5 and 6). It has been shown in this work that sulphur dioxide has a much greater effect than other sulphurous gases; in addition to increasing the scaling losses it will also promote the absorption of sulphur by the steel, the attack being localized and proceeding by way of the grain boundaries. Both sulphur dioxide and hydrogen sulphide react with the oxides of iron at high temperatures to form an

oxysulphide eutectic, which has a comparatively low melting point—about 950°C .—and is, therefore, molten at the heating temperatures usual for hot

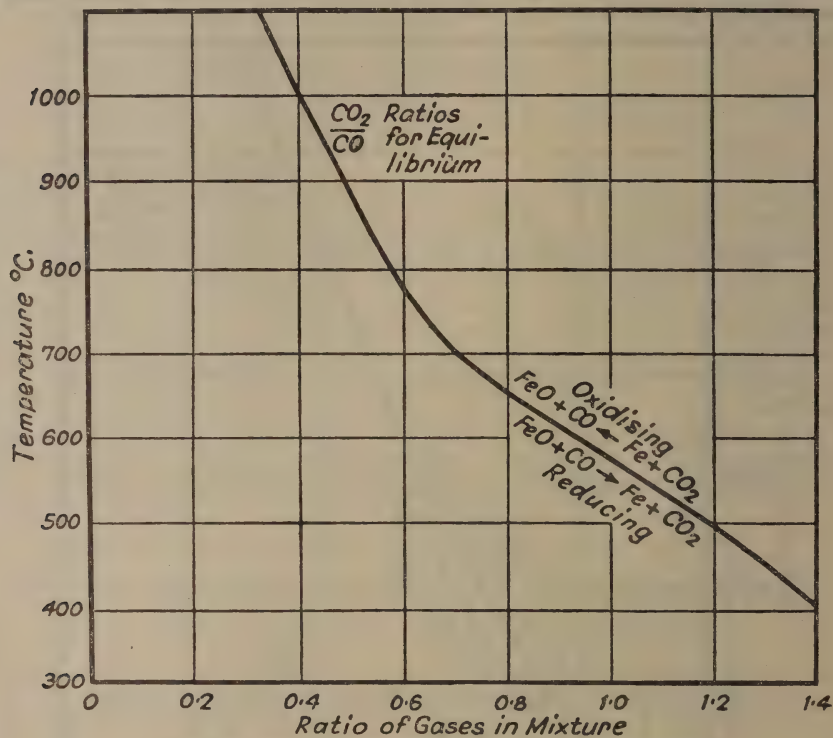


FIG. 3. Reduction of iron oxide by carbon monoxide.
(Austin and Day)

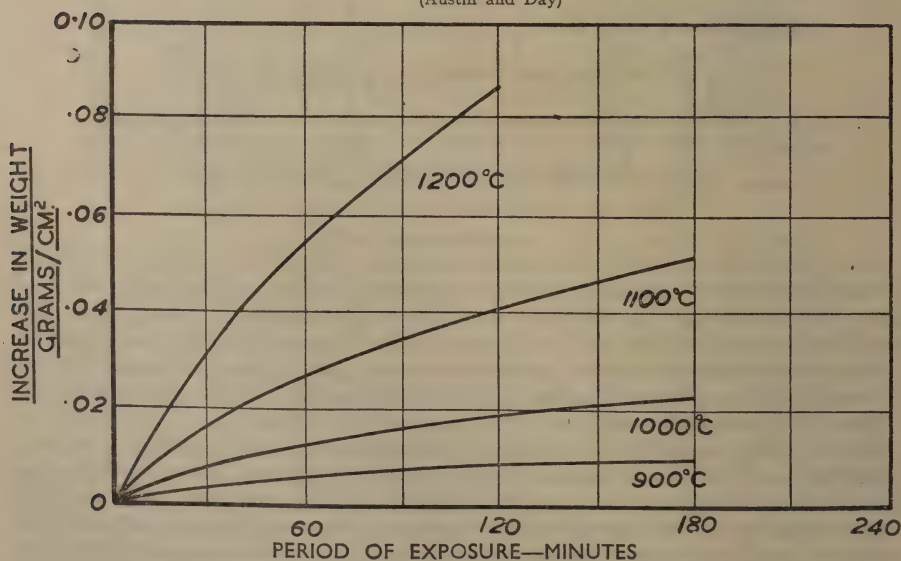


FIG. 4. Rate of scaling of mild steel in a neutral atmosphere.
(H. C. Millett and J. W. Cobb, *Trans. Inst. Gas Eng.*, 85, 672.)

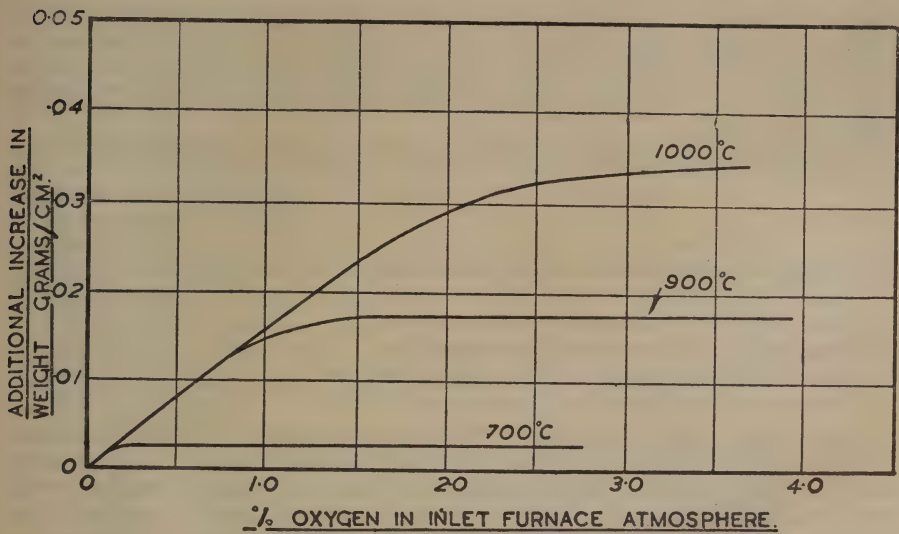


FIG. 5. Additional scaling of mild steel due to presence of free oxygen.
(H. C. Millett and J. W. Cobb, *Trans. Inst. Gas Eng.*, 85, 675.)

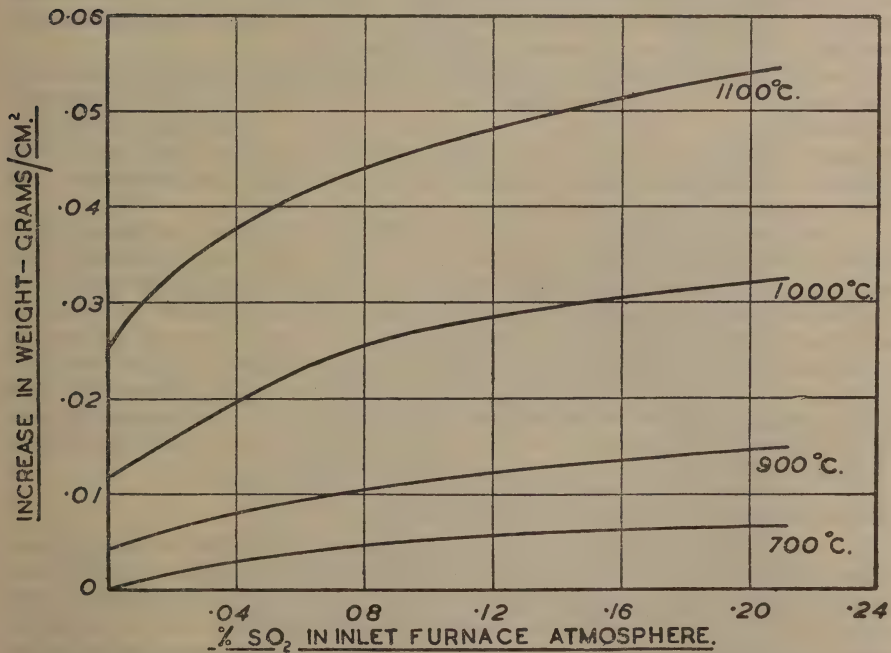


FIG. 6. Additional scaling of mild steel due to presence of free sulphur dioxide.
(H. C. Millett and J. W. Cobb, *Trans. Inst. Gas Eng.*, 85, 671.)

working. It is found below the layer of scale, and in its presence the extent of oxidation is two to three times as great as that obtained in a similar desulphurized atmosphere. To counteract the effect of the active gases on the oxidation of mild steel, for example, the atmosphere must contain carbon monoxide and hydrogen, firstly in sufficient quantity to ensure that the stable sulphurous

gases are converted to hydrogen sulphide, and secondly in concentrations, relative to carbon dioxide and water vapour, such that oxidation is reduced to a minimum. At high temperatures such necessary concentrations may be so high as to make the process entirely uneconomical in an internally heated furnace chamber.

The quantities of sulphur dioxide present in furnace atmospheres are as follows :

	<i>SO₂ in furnace atmosphere :</i>			<i>per cent.</i>
Purified coal gas (30 gr. S per 100 cu./ft.)	0.01
Coke (1% S), burned with no excess air	0.07
Fuel oil (1.5% S), burned with no excess air	0.09
Coke (2% S), burned with no excess air	0.14
Coal (1.5% S), burned with no excess air	0.15
Uncleaned coal gas (600-700 gr. S per 100 cu/ft)	0.20

It has been shown that the tenacity of scale is greater in so-called reducing atmospheres. It is well known that if a scale becomes "sticky" and troublesome in practice, in subsequent forming operations it can be readily made loose by a slight increase in the oxygen content of the furnace atmosphere, to a value of about 1 per cent. [Bright annealing referred to below is a somewhat specialized branch of furnace technology designed to entirely eliminate scaling, decarburization, or any condition that may impair the surface of the material heated. It is essential to use the muffle principle, in which the protective gas, specially generated, is circulated. (Jenkins *loc. cit.*)]

So-called reducing atmospheres can, therefore, be obtained by so adjusting the character of the air admission that a small quantity of carbon monoxide is produced in the furnace gases. Particular attention is directed to this fact because experience shows that many furnace operators may pass large volumes of unconsumed gas through the furnace under the impression that it will produce a reducing atmosphere.

It has been established that carbonaceous particles such as smoke exert little or no reducing action in a furnace. In order that any substance shall exert an effective reducing action it must be brought into contact with the oxidizable materials in the furnace. The molecules of a gas are in a state of very rapid motion; the molecule of hydrogen, for example, travels at the rate of one mile per second at ordinary temperatures. Molecules of gases thus come into contact with adjacent surfaces more freely and more frequently than (solid) particles of carbon, which are conveyed through the furnace by slow and comparatively gentle convection currents. Contrasted with the motion of gases, smoke particles are relatively almost stationary.

Bright Annealing. Externally heated furnaces

For the bright annealing of metals, a carefully controlled reducing atmosphere is essential. The primary object of most heat treatment operations is to attain a metallic structure having certain desired physical properties; the deleterious effect of the furnace atmospheres on the surface of the metal being treated has been decreased for the relatively cruder operations of internally heated furnaces in the manner described. One of the objectives of bright annealing is to eliminate scaling, decarburization, and other chemical reactions usually due to sulphur or oxygen, which impair the surface of the metal. The problems of bright annealing vary with each metal used, and the composition of the furnace atmosphere may have to be different for each metal.

There are very few metals or alloys that cannot be bright annealed, but the problem is more difficult with some than with others. For stainless steels

with a high percentage of chromium, the atmosphere must be completely free from oxygen and from oxygen-containing gases. Immunity from attack possessed by this class of metal depends on an invisible film of oxide that would be broken up by further oxidation. For the bright annealing of steel also, there must be no oxygen present and the ratio of oxidizing gases to reducing gases must be outside certain critical values. The problem demands a greater refinement in arrangements for producing a furnace atmosphere than does the scaling of ordinary mild steel already discussed.

The necessary exact control of the atmosphere cannot be attained if the combustion gases circulate in the furnace, which must be heated indirectly, and the gases that are to constitute the furnace atmosphere must be produced separately in an ancillary apparatus.

The oxidation of bright steel is preventable by keeping the ratios: CO_2/CO ; $\text{H}_2\text{O}/\text{H}_2$; $(\text{CO})/(\text{H}_2\text{O})/(\text{CO}_2)/(\text{H}_2)$; $(\text{CO})^2/(\text{CO}_2)$ above or below certain limits, the values of which depend on the temperature. (See Figs. 7 and 8.)

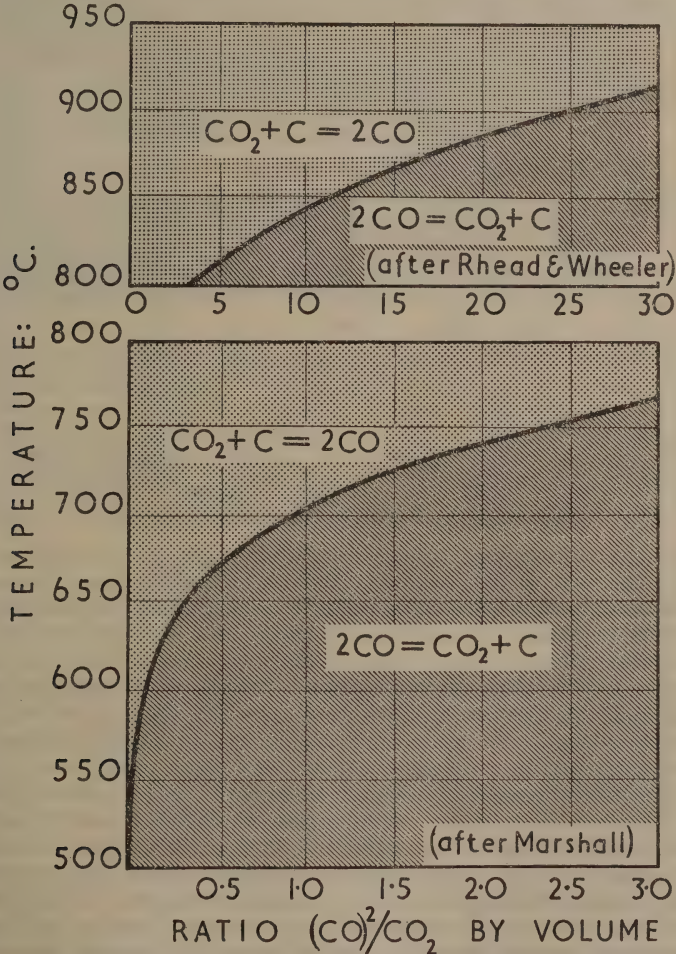


Fig. 7. Equilibrium curves for the reversible producer gas reaction $\text{CO}_2 + \text{C} = 2\text{CO}$. The gas composition at any temperature is that indicated by the curve.
(With acknowledgments to the *G.E.C. Journal*, XII, No. 1.)

In general, there is now no difficulty in partly burning gas so that the resultant atmosphere satisfies the required conditions of composition. The most careful control must be exercised over the combustion of gases in a furnace when products can be affected by the furnace atmosphere.

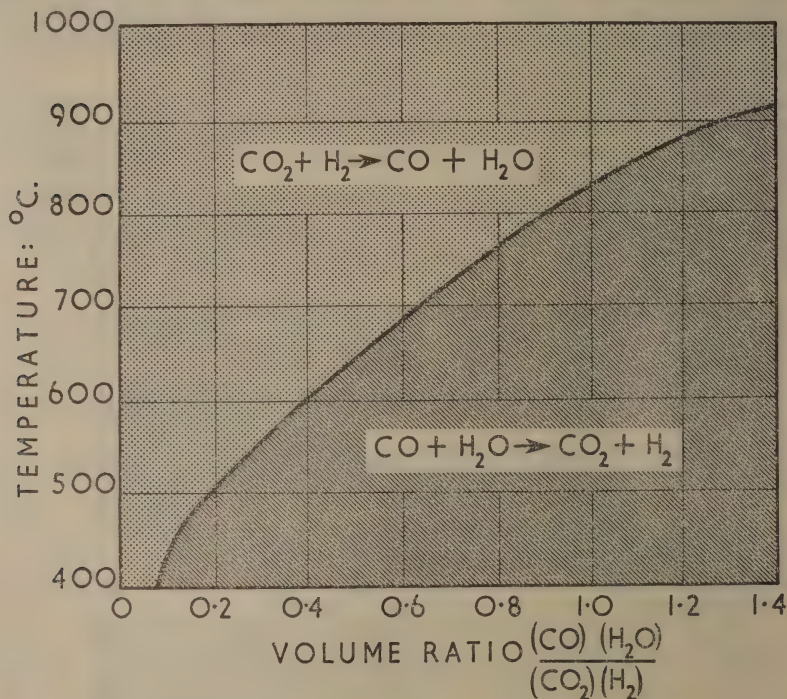


FIG. 8. Equilibrium curve for the reversible water gas reaction $\text{CO}_2 + \text{H}_2 = \text{CO} + \text{H}_2\text{O}$. The gas composition at any temperature is that indicated by the curve.

(With acknowledgments to the *G.E.C. Journal*, XII, No. 1.)

Special burners have been patented for this purpose; in these, gas and air are fed into the system by power-driven blowers with vernier proportioning control. These mixers govern both quantity and quality of the gas and will control the CO_2 content, for example, to within 0.5 per cent. In this type of equipment, the unit may be pre-calibrated by analysis of the purging gas so that the correct conditions for the bright annealing of a variety of materials can be achieved without trouble by a simple setting with a pointer.

Water vapour must be eliminated; it is removed by absorption in silica gel. The gases are burned in a refractory-lined combustion chamber and give up part of their heat by passing in counter-current to the air used for drying the silica gel chambers. The partly cooled gases are then passed through a condenser and further cooled to atmospheric temperature to remove the bulk of the water resulting from combustion of hydrogen. They are then dried by silica gel and passed through iron oxide boxes for removal of sulphur. Silica gel absorbs the last traces of water and is revived by passing hot air over it. A slight positive pressure must, of course, be maintained in the furnace to prevent ingress of air.

There are many alternative methods of producing the necessary atmosphere, as for example, by the decomposition ("cracking") of ammonia.

COMBUSTION AND HEAT TRANSMISSION

Although, with modern methods of mechanization and heat recovery, the use of gaseous and liquid fuels for the heating of furnaces gives marked improvement in thermal efficiency, the use of solid fuel must also be considered. Furthermore, developments in solid fuel firing are moving rapidly towards mechanization. Accordingly, coal firing in furnace practice must be considered in terms of the use of the mechanical stoker. In the combustion chamber conditions of metallurgical furnaces, where the temperature is kept above 750°C ., below which smoke particles remain unburned, an almost ideal condition of combustion can be obtained at all stages of the heating operation. To bring about such good conditions, ready control of primary and secondary air and flexibility in the coal feed are essential. Solid-fuel-fired furnaces, whether hand-fired or mechanically-fired, or with a built-on producer interposed, are limited in their efficiency because firing must of necessity be from one end of the furnace chamber. In general, a requisite for efficient performance is the rapid attainment of uniformity of chamber temperature. Powdered coal firing of furnaces is practicable, particularly if high intensities of heating are necessary. An obvious disability, which can be overcome, is the deposition of coal ash on the charge and the possible excessive slagging of refractories.

COMBUSTION AND FLAME CONTROL

Efficiency of combustion is bound up with the maintenance of the suitable atmospheric conditions in the furnace. Actual furnace temperature level, and uniformity of temperature throughout the furnace, together constitute the most important factors to be controlled. Rate of fuel input, flame characteristics, and conditions of draught are the pertinent agents of such control. The ideal means is a combination of instrumentation involving measurement of temperature, the control of the rate of fuel consumption from the results of this measurement, coupled with control of air/fuel ratio and of draught, regulated from the measurement of the furnace pressure. Where the more complicated instrumentation is not called for, simpler methods of control may be applied, given the necessary skill and judgment in the adjustment of the controls. Thus a flame may be set by its appearance, and draught may be regulated to meet the balanced condition resulting if hot gases are not blown out and cold air is not drawn in at a suitable small sight hole in a furnace door.

CLASSIFICATION OF FURNACES

Furnaces may be classified according to their mode of operation and purpose. No rigid terminology for this purpose has been developed, possibly because particular industries have, from experience, found specific types to be most useful. It is convenient however to recognize certain distinctions. They might, for example, be grouped within a class according to temperature level of operation. A functional grouping, applicable to the metallurgical industries, would be: melting, re-heating and heat treatment furnaces. A glass industry grouping distinguishes tank and pot furnaces and lehrs. There are biscuit and enamelling ovens and intermittent and continuous kilns in the pottery and heavy clay industries. In a multitude of other industries there are such specialized types as—amongst the shaft furnaces—the blast furnace, lime kiln and cupola, the last-mentioned with either cold or hot blast. The rotary kiln of the cement industry is an example of sintering furnaces. The chemical industry also provides many instances of special types of varied form and purpose.

It is usual to denote the main groups as to mode of operation viz. employing batch, continuous or muffle heating. In the realm of heat recovery there are the classes of recuperator and regenerator furnaces. A recuperator is a type

of heat exchanger in which the waste gases, and air or gas for pre-heating, are separated by a heat exchanging surface. It may be of refractory construction or, built up of tubes or plates of suitable heat-resisting alloys or alloy steels. A regenerator may be defined as a heat exchanger with a capacity for periodic storage of heat. It consists of a series of chambers containing refractory chequer work, through which the heating gases and the air to be heated are alternately led in opposite directions by means of a system of flues and reversing valves. The chequer work serves as the means of heat storage.

Heat Transmission and Gas Flow in relation to Furnace Design

The successful performance of any furnace depends upon these essential factors; behaviour of the fuel during combustion (particularly in respect of mode of heat release), the character of the flow of the hot gases through the furnace system and the mode of heat transmission in the furnace structure and the charge.

Heat Input

All the factors relating to the determination of the heat input, the properties and heating values of the fuels, sensible heat of air and fuel pre-heat, the heat content of the gases at any point in the furnace system, provided the temperature is known, are ascertainable with accuracy. The relevant criteria have been explained in earlier chapters.

Flow of Gases

The aerodynamical factors involved have been discussed in Chapter 10 (Flow of Fluids). Within a heated furnace chamber the influence of turbulence—an important operative factor—is still incompletely understood with respect to heat transmission, though useful qualitative guidance as to the change of the gaseous flow may be derived from the use of models on the basis of dimensional analysis.

Heat Release from the Flame

The heat release from the flame involves the phenomena of both luminous and non-luminous radiation. At present, the latter is the more completely understood, as may be evident from reference to Chapter 9 (Heat Transmission). The effective emissivity in coal flames, including both luminous and non-luminous radiation, is related to the excess air used in combustion by a logarithmic relationship, the radiation being greater in the presence of less excess air. The fundamental factors involved for a particular fuel are the air/fuel ratio, and the aerodynamical conditions produced by the combustion appliance. It cannot, however, yet be said that understanding of this facet of the problem has been advanced sufficiently far to enable a regime to be drawn up for design purposes. Further, the complexity of the subject involved in the determination of the re-radiation from the surfaces of the furnace and of the charge place it beyond the compass of this book.

HEATING OF THE FURNACE LOAD AND STRUCTURE

The amount of heat transferred to the furnace load and structure depends on the properties of the heating agency, in particular on its radiant properties, and on the temperature differences pertaining. The rate at which the stock and structure heat up is determined to some extent by the diffusivity of the particular materials used. Typical values are shown in Table 1 giving the comparative figures for metallic and refractory materials.

TABLE 1

<i>Metal</i>	<i>Conductivity:</i> <i>B.t.u./sq. ft. hr.</i> <i>deg. F./ft.</i> <i>thickness</i> <i>k</i>	<i>Specific heat :</i> <i>B.t.u./lb./deg. F.,</i> <i>over range</i> <i>0–600° F.</i> <i>s</i>	<i>Density</i> <i>lb./cu. ft.</i> <i>ρ</i>	<i>Diffusivity</i> <i>sq. ft./hr.</i> <i>$\frac{k}{\rho s}$</i>
Copper	220 (200–1,000° F.)	0·11	558	3·58
Aluminium ..	135 (at 600° F.)	0·24	168	2·68
Brass	66 (at 600° F.)	0·092	530	1·37
Wrought iron ..	35 (at 200° F.)	0·12	458	0·64
Cast iron	26 (at 200° F.)	0·13	442	0·44
Mild steel	25 (at 200° F.)	0·115	488	0·45
Firebrick	0·6 (at 600° F.)	0·23	125	0·024

In most heating processes, the heat transfer takes place in unsteady conditions where formal calculation of the quantities involved is complex. To obtain solutions of the equations applicable to the different cases recourse has been made to mechanical integrating machines, electrical analogue calculators and more recently to numerical techniques that can be performed on conventional calculating machines. Such methods are comparatively simple in application, but fraught with difficulties for the uninitiated. The reader is referred to the great wealth of information contained in the literature on this subject.

Practical rates of heating have been given by several authors. A useful parameter is the hearth loading in lb. per sq. ft. per hr. Approximate figures applying to iron and steel, and depending on dimensions of section and character of the metal are given below for different types of furnace.

<i>Type of furnace</i>	<i>Hearth loading</i>
Heat treating	15–30 lb./sq. ft. hr.
Annealing	30–60 do.
Forging	20–80 do.
Continuous furnaces	60–120 do.

The thermal efficiency of any furnace is closely linked with the hearth loading, being low when the hearth area is inefficiently utilised.

Other empirical rules, arrived at as a result of practical experience, are of great value. Thus the heat flux penetrates mild steel at the rate of $\frac{1}{8}$ in. for every five minutes. High alloy steels require, for heating time, at least one hour per inch of linear section, having generally a lower thermal conductivity than carbon steels ; slow heating is the rule up to 500° C. and the rate of heating can be speeded up at higher temperatures.

The practical points of control in arriving at efficient working are as follows :

- (1) The effect of different methods of disposing the charge should be tried until that which gives the maximum output per unit time is obtained.
- (2) The mass of the charge should be varied, if the operation admits of such a procedure, until a point at which an increase of weight per unit area of hearth either disturbs the final desired distribution of temperature at the finishing point or the rate of output becomes reduced. Generally the limiting factor is determined by the nature of the operation, and undercharging is more common than overcharging. The ideal hearth area for a specific duty should be sought. Much fuel can be wasted in wrong-sized furnaces.
- (3) The rate of firing should be changed experimentally until the optimum conditions are found, and then valves and dampers should be marked to show the ideal settings.

SOURCES OF HEAT LOSS IN FURNACES

Fig. 9 summarizes the movement of heat in a furnace². The heat is generated in the combustion chamber at the left, and travels from there to the right. The passage of heat into the stock, as indicated by arrows (1), is desired. But heat also goes elsewhere; some of it passes into the furnace walls and some into the hearth, increasing their temperature as indicated by the arrows (3). Another

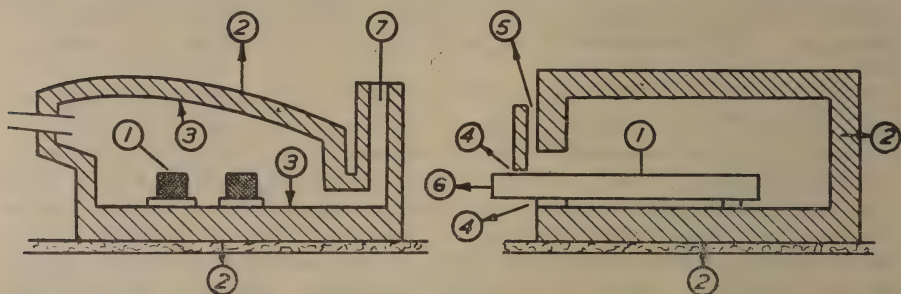


FIG. 9. Heat transmission and heat losses in furnaces.

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portion of the heat is lost to the surroundings by radiation and convection from the outer surface of the walls, or by conduction into the ground (2). Through cracks or other openings, heat radiates away (4); and furnace gases pass out around the door (5), frequently burning in the open, and carrying off heat. Then there are the special losses, peculiar to certain types of furnace; for example, in furnaces which heat only part of a long piece of metal, heat passes out along the metal from the part which is in the furnace to the part which is outside, and is there dissipated to the surroundings (6). Radiation from the exposed liquid surface of salt baths or lead baths, and conduction of heat through the terminals or electrodes of electric furnaces, are other cases in point. Water cooling of skid pipes and of conveyor rollers absorbs large quantities of heat and lowers thermal efficiency. If the charge is heated in containers or on travelling chains, a large part of the heat is dissipated in the open by these devices, after they have been brought up to furnace heat. Finally, heat passes out with the products of combustion (7), either in the form of sensible heat or as undeveloped heat of combustibles escaping unburned (incomplete combustion).

THERMAL EFFICIENCY

Definition of *thermal efficiency* for a particular furnace is liable to complications; in certain cases the heat supplied to the stock is used to effect chemical or physical changes involving actual changes of composition or the phase of the constituents of the materials. Consequently all the heat does not necessarily produce an immediate or sensible effect on the temperature of the stock. The term as used in boiler technology is not necessarily applicable to furnaces because of the different purposes for which heat is used. In a boiler, heat is applied to water for the purpose of converting it into steam which is used in that condition. In a furnace, the heat is given to a substance not only for the purpose of raising its temperature, but also in order that certain chemical or physical changes shall take place in the material.

In the burning of bricks, for example, not only is it necessary for the material to be raised in temperature to, say, $1,500^{\circ}\text{C.}$, but a certain time must be taken over each of the stages in order that (a) the shapes may be dried without cracking, (b) carbonaceous matter contained in them may be oxidized, and

(c) clay may be converted into mullite, or (with silica bricks) quartz may be converted into tridymite and cristobalite. (See Chap. 23.) The process requires that the temperatures shall be attained slowly and shall be held for a period which may be measured in days.

In the carburizing of mild steel the useful heat employed in raising the steel to carburizing temperature is only a part of the process; during by far the greater period when the steel is in the furnace there is no heat flow to the steel, since the diffusion of carbon in steel is a reaction requiring only time at a particular temperature, and not additional heat, for its completion.

Another example is the salt bath treatment in the normalizing of certain aluminium alloys. Little heat is required to raise the metal to its normalizing temperature, 495° C., and the transfer takes place very rapidly; thenceforth the process requires that a temperature of 495° C. shall be maintained in order that the necessary changes can take place in the metal. The heat required by the charge during this second stage is very small indeed, and fuel is required essentially to make up for the heat loss from the salt bath.

In these examples the efficiency of the appliance bears no relation to the real efficiency of the process.

For boilers, the thermal efficiency can be expressed thus:

$$\begin{aligned}\text{Boiler efficiency} &= \frac{\text{heat in steam}}{\text{total heat input}} \\ &= \frac{\text{Total heat input} - (\text{flue loss} + \text{surface loss})}{\text{total heat input}}\end{aligned}$$

But the efficiency of a furnace may be usefully related to the real work done by means of a criterion, the *fuel ratio*, expressing the ratio of the quantity of work done (e.g. metal heat-treated) to the total fuel consumption or its thermal equivalent,

$$\text{i.e. fuel ratio} = \frac{\text{quantity of work heat treated}}{\text{total fuel consumption}}$$

Thus the expression thermal efficiency as a general criterion for furnace operations is meaningless and each operation must be considered on its merits. It is for this reason that the figures obtained in calculating thermal efficiencies are often very low, not because of inefficiency, but because of the characteristics of the process. This, however, does not mean that there is not a great deal of inefficient operation in furnaces and that the low heat efficiencies often obtained cannot be very materially improved by making use of the principles of fuel technology. They can.

HEAT BALANCES

As examples of the heat balances of furnaces and as indicating the distribution of the heat, there are reproduced in Table 2 details of heat losses from furnaces. They are illustrative of conditions that may be improved upon.

Certain items involved in the heat balance are unavoidable heat losses. Inevitably there would be a significant heat content of the waste gases. For example, a small intermittent forge furnace heating steel to 1,200° C. must operate with the waste gases leaving at a higher temperature; in a continuous re-heating furnace the temperature of the exit gases will be much lower because the stock is charged cold. All this heat need not be lost if efficient methods of waste heat recovery are available, using such devices as recuperators, regenerators and waste heat boilers. (See Chap. 21.) Some sensible heat, however, is bound to be present in the gases, since it is not an economic proposition to cool below certain temperatures that are necessary if natural draught is used

to remove the gases. Latent and sensible heat of the water from combustion and evaporated from the material being heated in some cases, must always be lost.

TABLE 2. DISTRIBUTION OF HEAT LOSSES IN SOME FURNACES.

Type of furnace	Cer- amic kiln	Producer gas fired recuper- ative billet heating	Non- continu- ous re- genera- tive gas-fired heating	Oil- fired forge	Coke- fired forge	Coal- fired annea- ling	Recuper- ative gas-fired reheat- ing
Source of loss ..							
1. Useful heat trans- ferred to charge ..	14	23	40.9	9	16.1	18	48.7
2. Combustion and chimney losses							
(a) Unburnt combus- tible ..	3	2.6	2	3	5	5	1.0
(b) Sensible and latent heat in waste gases ..	50	22.4	26.7	47	52.3	45	3.9
(c) Gas generation loss in producer gas fired furnaces ..	—	15.0	—	—	—	—	—
3. Furnace structure in brickwork and heat lost to surroundings ..	33	37	30.4	41	26.6	32	46.4

There is always a loss by heat transfer from the external structure because the temperature of the structure will be higher than that of the atmosphere. The amount of heat lost in this way can and should be greatly reduced by proper insulation of the furnace structure. The sensible heat of the stock that is being heated may not be recoverable, though the heat content of the product may in some cases be used, as for example in brick kilns, for drying, and at some coke oven installations. (See : Dry Quenching of Coke, Chap. 3.)

The aim of good practice should be to reduce to as low a level as possible the quantities that can be regarded as a waste of heat, namely, undue losses in the flue gases, unnecessary losses arising from the structure, flaming out, radiation through gaps, ill-fitting doors, air infiltration and inefficient hearth utilization.

METHODS OF HEAT RECOVERY

The merits of installing a particular form of heat recovery appliance, even though the sensible heat of the waste gases may be high, is closely related to the size and character of the operation for which it is to be used. In general, recovery methods become a more practical consideration where a large installation such as an open hearth furnace or a battery of coke ovens is involved.

There are three ways in which the recovery may be effected :

- 1. recuperation,
- 2. regeneration,
- 3. waste heat boilers.

The first two methods have been briefly referred to at the beginning of this chapter. Waste heat boilers are dealt with in some detail in Chap. 21. Recuperation and regeneration are usually applied to pre-heating the air for combustion and, with the leaner gaseous fuels, pre-heating the fuel as well. In this way the flame temperature will be raised and heat transfer will be increased. The relative methods of pre-heating the air used in conjunction with different fuels are given in Table 3 adapted from Table III, "Problems in Fuel Efficiency."³

TABLE 3
AIR PRE-HEATING: CHARACTERISTICS OF FUELS

<i>Fuel and Heating Value B.t.u./lb., or B.t.u./cu. ft.</i>	<i>Coal</i>	<i>Fuel oil</i>	<i>Coke oven gas</i>	<i>Producer gas</i>	<i>Blast furnace gas</i>
	(a) 14500 (b) 12750	18,700	475	163	92
Air required to burn 1 lb. of fuel: lb. ..	(a) 10.1 (b) 7.1	14.0			
Do. cu. ft. at 60° F. ..	(a) 132 (b) 116	184			
Air vol./Gas vol. . . .			4.06	1.28	0.69
Vol. required for release of 1,000 B.t.u. :					
(x) air — cu. ft. . . .	(a) 11.0 (b) 11.0	9.85	8.55	7.85	7.50
(y) waste gases — cu. ft.	(a) 11.7 (b) 11.9	10.4	10.0	12.7	16.7
B.t.u./cu. ft. of products ..	(a) 86 (b) 84	96	100	79	60
Sensible Heat as % of Gross Heat					
at 1,200° C. . . .	(a) 48.3 (b) 49.3	46.8	48.1	65.6	79.1
at 600° C. . . .	(a) 21.7 (b) 21.5	21.5	20.9	29.8	34.2
(z) Potential Heat available for Recovery in Cooling of Gases from 1,200° C. to 600° C. per cent. . .	(a) 26.6 (b) 27.8	25.3	27.2	35.8	44.9
Relative Index of Air Preheat obtainable ..	(a) 27				
(y) × (z) ÷ (x) ..	(b) 30	27	32	58	100

Further useful information is given graphical form in Figs. 10 and 11.

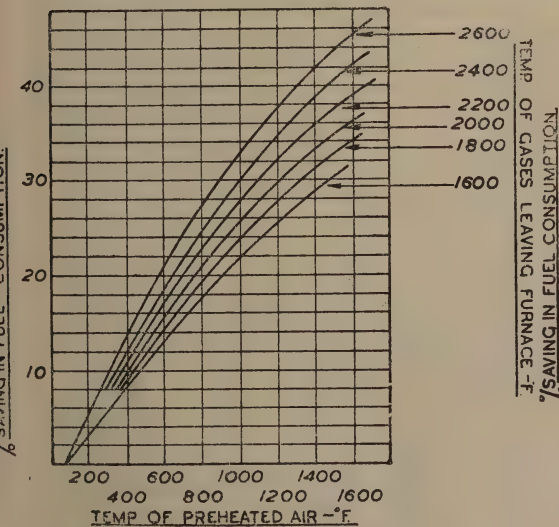


FIG. 10. Saving of fuel in powdered fuel furnaces gained by preheating the air for combustion.

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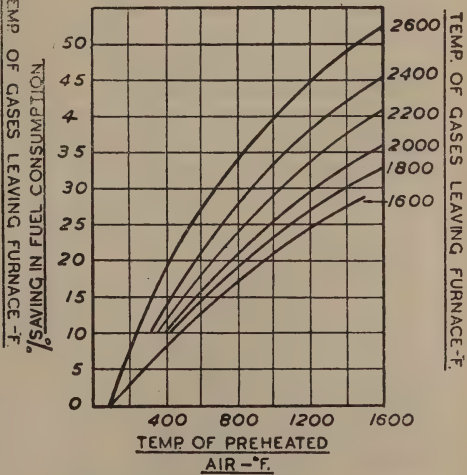


FIG. 11. Saving of fuel in producer gas fired furnaces gained by heating the air for combustion.

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A recuperator is a heat exchanger between the waste gases and the gas to be preheated. It usually consists of a system of ducts or tubes some of which carry the air for combustion to be preheated, the others containing the source of waste heat. Heat interchange takes place between the fluids. Figs. 12, 13, 14 show different heat interchange systems, counter-flow, parallel flow and cross flow with typical temperature curves. The recuperator may be of either metallic or refractory construction, according to the temperature and the corrosive properties of the waste gases involved.

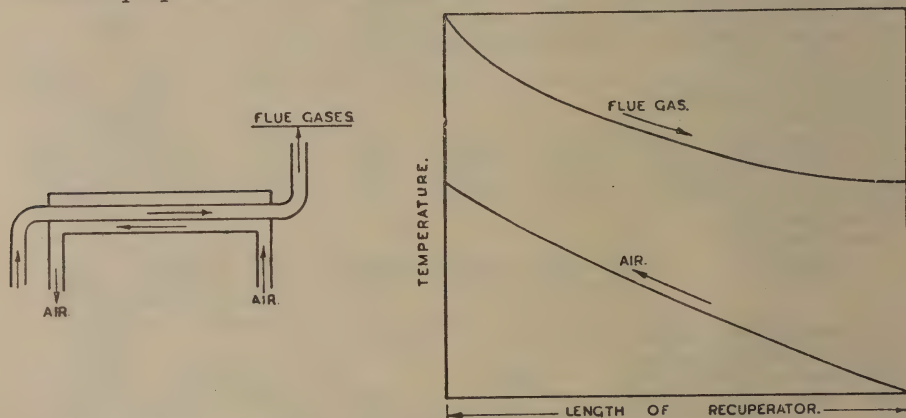


FIG. 12. Counter-flow recuperator and temperature distribution.
(Based on "Industrial Furnaces" by W. Trinks.)

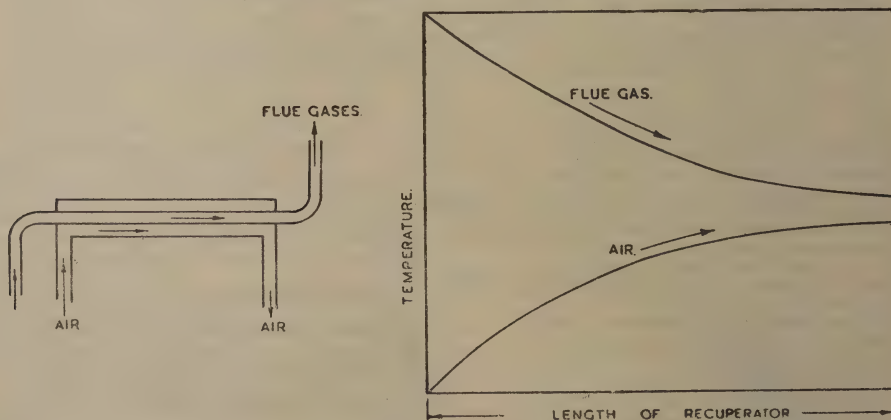


FIG. 13. Parallel-flow recuperator and temperature distribution.
(Based on "Industrial Furnaces" by W. Trinks.)

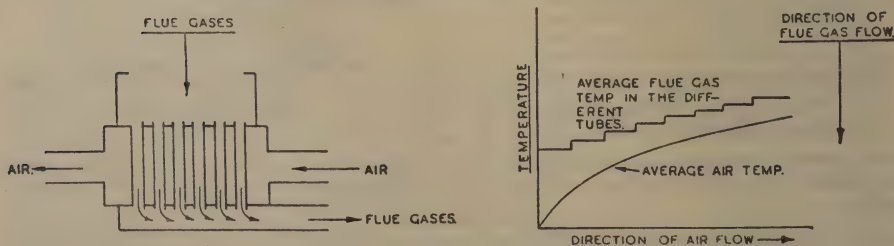


FIG. 14. Cross-flow recuperator and temperature distribution.
(Based on "Industrial Furnaces" by W. Trinks.)

The counter-flow type allows the highest temperature of pre-heat to be reached, whereas the parallel-flow type gives the lowest maximum temperature of the recuperator walls. It is frequently used in conjunction with metallic recuperator walls where the temperature must be kept comparatively low.

Recuperators depend on heat transferred by conduction through a wall of material between two streams of gas, and may be less efficient thermally than regenerators especially when constructed in brick. They have, however, the advantage that they do not require periodic reversal because they are fixed passages through which air and gas flow continuously.

A regenerator is a heat exchanger constructed of refractory material. Reference to Fig. 16, Chap. 9 will show that in its simplest form it comprises two chambers filled with chequer firebricks, the bricks being so stacked that the gases can flow freely between them and around them. If gas is burned, as shown, from the port on the left-hand side, the hot flue gases after doing their work in the furnace pass down the right-hand regenerator chamber and give up much of their sensible heat to the brickwork. The temperature of the brickwork decreases from top to bottom of the chamber. The air for combustion flows up the left-hand chamber. After some predetermined period, usually from 20 minutes to 30 minutes, a reversing mechanism changes the direction of flow of the gases. The gas is cut off from the left-hand ports and now admitted to the right-hand ports. The right-hand regenerator is disconnected from the chimney flue by closing a valve. The air is admitted to the base of the right-hand regenerator, and the flue gases pass down the left-hand regenerator. Thus the right-hand regenerator now gives up its stored heat to the incoming air, which is preheated, and the sensible heat of the gas is retained in the left-hand regenerator. After 20–30 minutes the flow is again reversed and the cycle is repeated.

An extension of the system permits alternate regenerator chambers to be used for preheating producer gas or blast furnace gas, the air being also preheated. (See also discussion in Chap. 9.)

Regenerator design is generally a compromise between the requirements of mechanical strength, freedom from choking due to dust or fume in the products of combustion, and heat transmission surface. Design has been dealt with in a number of publications^{4 5 6}.

The temperature conditions are analogous to those which occur in a counter-flow recuperator. From the standpoint of control there is already means of improving the efficiency of regenerators at rebuilds, since the change only involves modification of methods of stacking the regenerator chequer brickwork. The subject is beyond the scope of the present discussion, but merits close investigation on the part of all users of regenerators.

To combine increased heat-absorption surface with an economical use of brickwork, special shapes are sometimes used, but it is still uncertain whether such expedients are necessary in regenerators of adequate design.

Between 60 and 85 per cent. of the sensible heat removed from the waste gases during passage through a regenerator is transferred to the air and/or gas being preheated. Taking, however, the heat returned to the furnace by the regenerators via gas and air, as a percentage of the sensible heat in the gases reaching them, which constitutes the true thermal efficiency of the regenerative system exclusive of the flues, the maximum value realisable is of the order of 40 per cent., depending on the degree of preheat which is admissible.

For more detailed treatment of the problems of waste heat recovery in industrial furnaces the reader is referred to the volume cited ⁶.

INSULATION

The furnace wall has a threefold function: (1) to ensure the necessary refrac-

toriness to withstand the effect of the flame and the slagging action of the dust in the furnace atmosphere; (2) heat insulation; (3) in certain processes, to provide a means of supplying heat to the stock by re-radiation.

It is not always possible to obtain an ideal combination of these properties in any one material. Accordingly, a composite wall of firebrick and insulating brick may be used. The effectiveness of the insulating materials depends upon the minuteness and uniform distribution of the cells of air present in the material, the heat conductivity of which is extremely low.

The physics of insulation has been considered in Chapter 9 and the properties of insulating materials are discussed in Chapter 23. Here, only the practical application of the subject is considered. The temperature at which any insulating materials can be used is limited. When a refractory material forming a furnace lining is backed by insulation, the temperature of the outer surface of the refractory forming the interface between it and the insulation is raised, and so also is the average temperature of the brick. The interfacial temperature is the maximum temperature to which the insulation is heated and this must be less than the limiting temperature given in Chapter 23. Furthermore, as indicated in that chapter, the effect of insulation may be to bring the refractory within the danger zone at which it can

TABLE 4. INTERFACIAL TEMPERATURES AND HEAT LOSSES

Thickness of		Temperature of the hot face—° C.									
Fire-brick in.	Insulation in.	1,400	1,200	1,000	800	600	1,400	1,200	1,000	800	600
		Temperature at interface between firebrick and insulation: ° C.					Heat loss: B.t.u. per sq. ft. per hr.				
4½	—	420	350	310	250	190	5,400	3,600	2,850	2,000	1,130
4½	4½	1,235	1,060	880	705	530	670	530	410	300	210
9	—	280	240	200	160	125	2,400	1,850	1,400	830	540
9	2½	990	850	710	570	430	790	620	460	330	230
9	4½	1,120	960	800	640	480	560	420	320	230	170
9	9	1,240	1,065	890	710	535	320	240	190	150	100
13½	—	260	220	190	150	120	2,150	1,600	1,300	740	530
13½	4½	1,020	880	735	590	440	480	360	270	210	160
18	—	180	150	130	110	90	1,030	750	600	460	340
18	4½	950	815	680	550	410	420	330	260	200	150
18	9	1,120	960	800	640	485	280	220	180	140	100

Note: Where no insulation is used the temperature recorded is that of the external surface of the wall.

collapse under load. Losses of heat and interfacial temperatures are given for a number of constructions in Table 4. The insulation of furnaces is extremely important for fuel economy, but should be undertaken under expert advice.

INSULATION OF FOUNDATIONS

It is preferable to insulate hearths and foundations, particularly around flues, but below the insulated hearth there should be provided air ventilation, the hearth being separated from the foundations by an air gap. Otherwise the soakage of heat from large furnaces into the foundations may result in the concrete cracking from expansion.

CONTINUOUS AND INTERMITTENT FURNACES

There is a fundamental distinction between continuous furnaces which operate for weeks or months together at a virtually uniform temperature and those intermittent furnaces which require to be cooled to a greater or lesser degree between charges, and again heated to full temperature.

Both suffer losses by conduction, through the walls, of heat which escapes by radiation and convection from the outer surface. In both heat is required to raise the brickwork to working temperature. But whereas, in a continuous furnace as here defined, the heat stored in the brickwork is a negligible proportion of the total heat supplied to the furnace during its whole working cycle, in the intermittently heated furnace this heat, which is at least partly dissipated each time the furnace temperature is reduced, may be the greater part of the total heat supplied. The ratio of stored heat to total heat depends on the time cycle of the heating and cooling operation.

In continuous or long time-cycle furnaces the insulating problem is to prevent the dissipation of heat from external surfaces. In intermittent, short time-cycle, furnaces the chief problem is to reduce the heat storage loss, whilst not neglecting to mitigate the external surface loss.

The impression widely held that intermittent furnaces that must be cooled between operations should not be insulated is erroneous. The relatively new technique of hot-face insulation provides a means of saving much of the very serious losses that occur in intermittent furnaces through heat storage in the brickwork. Furthermore, there have been developed in recent years hot-face insulation materials that are resistant to much higher temperatures than were formerly available. This subject is discussed in more detail below.

HEAT REQUIREMENTS OF THE FURNACE STRUCTURE

When a furnace is heated up from the cold, the first stages involve the heating of the brickwork to the requisite temperature. It is frequently not realised what large amounts of heat are required for this purpose. The heat required over a period depends to a great extent upon the time cycle of the furnace. In a continuous furnace the proportion which the heat used for heating up bears to the total heat used in the furnace in a year is very small. It is high in the case of furnaces with weekly cycles, e.g. reheating furnaces, when they are not used at the week-ends. With a daily cycle, shutting down over-night (e.g. drop-forge furnaces and some heat-treatment furnaces) it may be very high. Finally, in furnaces operating on a heating-and-cooling cycle (e.g. annealing furnaces and intermittent brick kilns) in which the furnace is heated up with each charge of goods and cooled with the goods in, the heat consumption by the brickwork may assume quite surprising proportions in relation to the heat usefully consumed.

The heat stored in the brickwork is given by the product :

weight of brickwork (lb.) \times sp. ht. (B.t.u. per unit weight) \times average rise in temperature (deg. F.), the result being given in B.t.u.

The specific heat is practically the same for all siliceous refractories, including firebricks, silica bricks and insulating bricks. The rise in temperature depends on the conditions. The essential differences are in the weight of the bricks. Firebricks and silica bricks generally weigh between 100 and 130 lb. per cubic foot, whereas insulating bricks weigh about one-quarter of these figures. Thus, for a given temperature range, the heat stored in a wall of insulating bricks is only one-quarter of that stored in a similar wall of acid refractory—an argument in favour of using as much insulating brick and as little refractory brick as possible in the walls of intermittent furnaces.

To give some illustration of the quantity of heat used for heating up the brickwork to the steady state, the conditions tabulated in Table 4 have been used to calculate Table 5. Here the refractory is assumed to weigh 120 lb. per cubic foot; the insulation 30 lb. per cubic foot. The specific heat of both is regarded as 0.24. The temperature is calculated from a datum of 60° F.

TABLE 5

Composition of furnace wall		Mean temp. in wall				Heat stored in wall B.t.u./sq. ft. of internal surface		
Refractory in.	Insulation in.	Refractory ° F.	° C.	Insulation ° F.	° C.	Refrac- tory	Insula- tion	Total
9	nil	1,250	676	—	—	25,800	—	25,800
13½	nil	1,210	654	—	—	37,400	—	37,400
9	4½	1,829	998	945	507	38,200	2,400	40,600
13½	4½	1,765	963	877	470	56,200	2,220	58,420
9	9	1,902	1,040	988	531	40,000	5,020	45,020
13½	9	1,860	1,016	945	507	58,400	4,800	63,200

Clearly, the shorter the time cycle, the greater is the heat stored in the wall in comparison with the heat lost by conduction, etc., through the wall.

INTERMITTENT OPERATION

The first effect of external insulation is to increase the heat storage in the wall (Table 5) because the average temperature of the heavy refractory lining is increased. By putting 4½ inches of insulation on the exterior surface, the heat storage is increased by about 60 per cent. This is of no consequence in a continuous or long-cycle furnace, but becomes of great significance in a short-cycle intermittent furnace. The solution of the difficulty lies in reducing to a minimum the weight of refractory that must be heated and cooled each cycle. Until comparatively recently this solution was rendered impossible by the high temperature of the insulation/refractory interface, insulating materials not being available to withstand this temperature.

The newer technique of "hot-face" insulation has become possible through the development of bricks which combine high refractoriness with good insulating properties. It is now possible to construct furnaces wholly of these bricks, or line the interior with these bricks. Tables 6 and 7 indicate from published figures the value of hot-face insulation for intermittent furnaces. Table 6 shows the very much smaller quantity of heat stored in a wall constructed of high temperature insulating material. Table 7 compares the performance of an uninsulated intermittent furnace with a hot-face insulated furnace with single and double insulation.

TABLE 6. HEAT STORAGE IN RAISING HOT FACE TO 1,300° C. AND MAINTAINING TO GIVE FULL SATURATION⁷

Type of Wall	Thickness		Heat stored, B.t.u./sq. ft.			Relative proportions of heat stored
	Brick in.	Insulation in.	Brick	Insulation	Total	
Hot-face insulation . .	9	—	—	—	15,010	1
Firebrick backed with insulation	18	4½	86,600	2,730	89,330	6
	13½	4½	67,720	3,025	70,745	4.7
	9	4½	46,950	3,310	50,260	3.4

TABLE 7. FURNACE OPERATING AT APPROX. 1,000° C. OVER 120 HOURS
CONTINUOUS CYCLE WITH A WEEK-END SHUT-DOWN OF 48 HOURS
(*k*=thermal conductivity in B.t.u./sq. ft. hr. deg. F./in.)

Method of construction	9 in. firebrick <i>k</i> =7.8	9 in. hot-face insulation <i>k</i> =1.88	9 in. hot-face insulation, <i>k</i> =1.88 ; backed by 2 in. insulation, <i>k</i> =0.74
Loss by transmission through brickwork B.t.u./sq. ft./week ..	146,400	39,300	25,200
Heat capacity loss, B.t.u./sq. ft./week-end ..	20,090	6,540	6,810

Hot-face insulation can be used for a variety of purposes, one of which is for lining hot gas ducts. A producer gas main at a steelworks which had been so lined gave the following results :

	Before insulation.	After insulation.
Gas inlet	700° C.	730° C.
Gas outlet	460° C.	660° C.
Temperature drop along the main ..	240° C.	70° C.

The relatively low cold crushing strength of these bricks does not, as is sometimes supposed, preclude their use for large furnaces. The weight of the structure is very much reduced by using the lighter bricks and the reduced average temperature in the brick for a given hot-face temperature leads to a smaller reduction in the crushing strength with rising hot-face temperature when compared with firebrick. Brick kilns up to 31 feet in diameter with a total weight of crown of 14 tons have been in operation, using hot-face insulation, for the past eight years without major repairs; no important part of this structure is built of firebrick.

Figures obtained on a small gas-fired forge furnace are given in Table 8. No alterations were made in this furnace other than the substitution of 4½ inches of insulating lining in place of the same thickness of firebrick.

TABLE 8. EFFECT OF HOT-FACE INSULATION ON A FORGE FURNACE

	Firebrick lined	Lined with insulating brick
Time to reach 1,150° C. from cold	55 min.	15 min.
Gas used in heating up	400 cu. ft.	90 cu. ft.
Rate of consumption	475 cu. ft./hr.	375 cu. ft./hr.
Gas rate for maintaining working temperature at 1,150° C.	350 cu. ft./hr.	175 cu. ft./hr.

Finally, Table 9 indicates results claimed on a gas-fired annealing furnace operating at 750° C., in which an older furnace of normal design was replaced by a new furnace built of insulating refractory, with a non-refractory insulating backing.

Part of the improvement registered was due to the provision of instruments and controls.

TABLE 9. EFFECT OF USING INSULATION

<i>Heating up to 750° C.</i>	<i>Old furnace</i>	<i>New furnace</i>
Time	4 hr.	1 hr.
Gas used per heat	4,500 cu. ft.	750 cu. ft.
Gas used at six heats per week	27,000 cu. ft.	4,500 cu. ft.
Saving		22,500 cu. ft. = 83.3%
<i>Maintaining at 750° C.</i>		
Gas used at 44 hr. per week	33,000 cu. ft.	15,400 cu. ft.
Saving		17,600 cu. ft. = 53.3%

The quest for high output in intermittent furnaces has led to the practices of (a) constructing these furnaces of thin, uninsulated walls to reduce the thermal storage, and (b) regarding insulation as unwise; both practices are supposed to assist in rapid cooling and so to increase output.

These practices and beliefs are fundamentally unsound. Thin walls may be admissible for very short time cycles, but if the furnace is operated for longer than the limiting time corresponding to the thickness of the wall, these thin walls lead to a high external temperature and to great consequent waste of fuel.

Insulation—external or internal—is always an advantage even with intermittent furnaces which must be partly cooled internally between charges. The inside surface of the wall can be cooled rapidly by air (if suitable bricks are used) for the reception of cold stock, but the body of the brickwork remains hot and the furnace wall requires less fuel in the aggregate. The opinion that intermittent furnaces should not be insulated arises from ignorance of the true temperature gradients that remain in a furnace wall when the surface has been rapidly chilled.

Tables 8 and 9 indicate the much greater rate of heating up when hot-face insulation is used, as a direct result of the low heat capacity. For the same reason cooling is also accelerated, since the heat content of the brick is lower and the temperature gradient steeper.

In recent years, marked improvements have been made in the refractory materials available for hot-face insulation. These relate to the shape, strength at high temperature, refractoriness and resistance to spalling. It is now practicable to provide entire inside lining walls and crown, of materials having these superior properties and able to withstand the highest practicable operating temperatures, along with improved slag resistance.

When a furnace is closed down for a period daily or at the week-end, insulation will prevent heat losses and will enable the furnace to be started up again quickly and with little expenditure of fuel. In order that the maximum advantage may be derived from this effect, it is essential that the brickwork should be well pointed to avoid ingress of air, doors should fit tightly, and in particular the dampers must be tightly fitting so that no cold air is drawn through the furnace during the time it is closed down. Under good conditions it is possible to keep sealed-up furnaces hot for long periods. This is an alternative to banked fires or limited gas consumption that should be considered. For information on these features reference may be made to the paper on "Furnace Design and Practice" by Sarjant⁸.

RADIATION LOSSES THROUGH OPENINGS

Fig. 15 indicates a furnace in which there is a hole in the furnace wall. An observer at A would see the interior of the furnace as if that interior were a

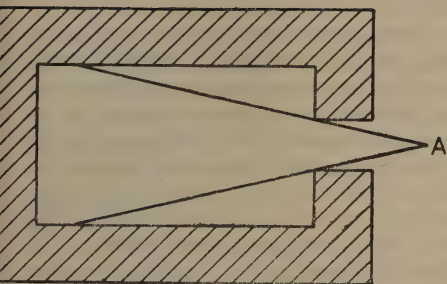


FIG. 15. Heat radiation from an opening in a furnace.

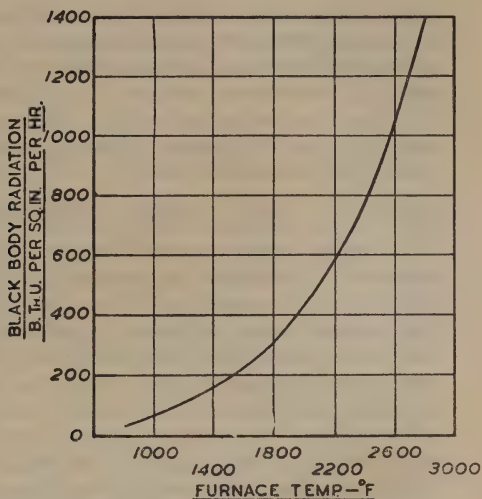


FIG. 16. Black body radiation from a furnace interior.

plane surface situated at the opening and having the same area as the opening.

Since the interior of a furnace is generally taken to be equivalent to black-body radiation ($\epsilon=1$) the rate of heat radiation per unit area of plane surface observed would be given by Fig. 16 for a furnace having walls of negligible thickness at the opening (see also Radiation, Chapter 9).

An example will illustrate the method of calculation. A furnace front is bricked up with a $4\frac{1}{2}$ inch wall, through which an observation opening (peep-hole) of $9 \times 2\frac{1}{2}$ inches is left open. It is required to calculate how much heat escapes through the hole by radiation if the furnace temperature is $2,400^\circ\text{F}$. ($1,315^\circ\text{C}$).

Area of equivalent diaphragm = $2\frac{1}{2} \times 9$ inches = 22.5 square inches.

From Fig. 16 black-body radiation from 1 square inch of surface at $2,400^\circ\text{F}$. = 800 B.t.u. per hour.

Heat loss from freely exposed diaphragm = 800×22.5
= 18,000 B.t.u. per hour.

This calculation is correct only if the furnace opening is constructed of very thin material. The result is too large because the thickness of wall obstructs the direct radiation to an extent depending on the ratio of the wall thickness to the width of opening; and it is too small to the extent to which the sides of the opening become heated by radiation received from the interior of the furnace, and re-radiate away from the furnace a part of the heat thus received. As a result of these errors the calculation just made gives figures of the order of double the real rate of loss of heat from an opening.

The figure of double just mentioned must not be taken as an invariable factor; it depends on the shape of the hole and the ratio of least width to wall thickness. A similar calculation shows that if in a furnace operating at $2,200^\circ\text{F}$., a furnace door measuring 5×4 feet is left open, heat is lost at the rate of 1,728,000 B.t.u. per hour, neglecting the factor. The factor here is 0.85, making a total loss of heat of 1,469,000 B.t.u. per hour. The calculations are more specialised than the treatment here demands and are given not for instruction in the method of making them, but to direct attention to the importance of keeping all openings in furnaces closed as far as possible. All apertures through which the furnace can be observed should be covered with

plates preferably backed by insulation.

In a furnace door which is opened periodically, continuous loss of heat does not occur, but the door lining and the sides of the opening become heated to practically furnace temperature. Thus whenever the door is opened there is the dual loss of radiation from the door and from the sides of the opening which are quickly cooled, plus the radiation loss due to the opening which has previously been calculated.

LOSS BY FLAME OUTSIDE THE FURNACE

In order to prevent oxidation of the charge in a furnace which must be operated in a reducing atmosphere, furnaces are frequently worked under pressure. It is considered that a slight loss by gases passing outwards is less detrimental than oxidation by air leaking inwards. If, however, the furnace door does not fit well, the volume of flame passing out of the furnace may be quite considerable. The door frame will be overheated and will become warped, and the conditions will be made worse. It is difficult to estimate the amount of loss from this cause, but it is evidently a source of loss to which close attention should be paid. Maintenance of the structural work and correct fitting of doors and covers, together with adjustment to as small a positive pressure as possible within the furnace, are the two ways in which this loss may be minimized. It has been concluded that with tightly fitting doors this loss may not exceed 2 per cent. of the total heat delivered to the furnace, and should not average more than 1 per cent. With loosely fitting doors, and with a flame or jets of heated gases projecting against the doors, it may easily reach 8 per cent. and at times may even exceed that amount.

This loss is especially heavy in large furnaces with ingots projecting under the door into the open, because large half-open doors cannot be made tight. Under these circumstances it is better to brick up the opening around the ingot.

A similar loss may occur through flames within the structure not being confined to the furnace chamber. It sometimes happens, when combustion is badly adjusted, that the flame passes through the furnace and continues to burn in the recuperators, regenerators, or waste gas flue.

If there are adequate arrangements for recovering the heat that is lost and this heat can be put to useful purpose, the result may not be very serious. If, however, the heat is not recovered the loss may be very great indeed.

Finally, in furnaces operating under pressure, open spy-holes or cracks in the furnace wall may cause a loss of gases by flame burning in the outside air.

It has been recorded, perhaps as an extreme example, that during the inspection of furnaces in the drive for fuel economy, instances have been noticed in which there appear to be nearly as much flame burning outside the furnace as inside. With injection burners in small furnaces this condition is often caused by excessive pressure cutting down the air supply.

SCIENTIFIC CONTROL

In any attempt at scientific control of furnace efficiency a primary knowledge of the distribution of the heat losses is essential. From the resulting heat balance it is possible to devise routine methods of control which will ensure that the controllable elements are regulated. (See Chaps. 26 and 28.)

THE HEAT BALANCE

The main elements of the balance sheet are :

(1) *Useful Heat Transference to the Charge.* This is readily obtained by a knowledge of the temperature, weight and character of the charge from which the heat capacity can be obtained. It entails recording the necessary informa-

tion of the weights charged, and accurate pyrometry, the importance of which in their bearing on economical furnace practice cannot be over-emphasized.

(2) *Combustion and Chimney Losses.* (a) Unburnt combustible, both in the products of combustion, as deduced from gas analysis, and in the ashes derived from solid fuels.

(b) *Sensible heat and latent heat in waste gases*, obtainable from determination of the CO_2 content of the waste gases and their temperature. Charts constructed for each fuel, as in Chapter 7, facilitate the evaluation of this loss.

(3) *Furnace Structure Losses.* Heat stored in brickwork and lost to surroundings is frequently obtained by difference. Its exact determination is difficult, but considerable information of value can be obtained by the determination of external surface temperatures. Excessive temperatures, besides indicating excessive surface losses due to insufficient thickness of refractory lining, point to breakdown of insulation and defective brickwork.

The subject of Heat Balances is dealt with in greater detail in Chapter 26.

INSTRUMENTS

The instrument panel on a furnace should be the nerve centre of the installation. It should indicate at all times the rate of input of heat to the installation and whether the combustion and draughting conditions are correct. In the smaller types of plant draught gauges and pyrometers may have to suffice. The air consumption can be made an index of the heat input. Its measurement by means of an orifice gauge, a simple and inexpensive type of instrument, offers a ready means of control on any type of furnace. Safeguards must be taken to avoid inleakage of cold air, which can vitiate the indications of the flow meter.

INSTRUMENTATION AND CONTROL

The most significant features of the modern developments in furnace practice relate to the mechanization and the application of automatic control. Such advances have been applied to better methods of transport of materials throughout the particular heating process and more efficient control of the combustion and draughting from the actual furnace instruments.

Effective instrumentation has been applied in the following ways:

(a) *Temperature Control :*

The fuel feed rate to a particular furnace may be controlled from temperature measuring instruments, e.g. radiation pyrometers and roof temperature controllers in the case of open hearth furnaces.

(b) *Combustion Control :*

This is the regulation of the air/fuel ratio by flow meters, coupled by servo mechanism for automatic control of valves. These may then be automatic.

(c) *Draught Control :*

Slight changes in furnace pressure may be made to activate a sensitive mechanism which, in turn, activates the main exhaust gas damper by electrical, pneumatic or hydraulic power amplification. This may then be made into a master controller, maintaining balanced draught operating both the input and output of the furnace gases.

In general one master controller should be used and it should be regarded as an essential feature of the furnace unit. Further information is given in Chap. 28.

RECORDS OF PERFORMANCE

The first essential towards attaining control of fuel economy is to keep regular records of the data for watching efficiency. These include routine

recording of the fuel used, the output, the hours worked, the variations of shop conditions, and of any special tests carried out on individual furnaces. Charts of the performance of furnaces should be drawn and kept under constant observation. If the rate of fuel consumption is plotted against the rate of output a straight line relationship is generally found; when produced to cut the fuel consumption ordinate at zero output this gives the rate of consumption for the empty furnace. This represents the quantity of fuel required per hour, say to bring the furnace to temperature, and maintain it in operation under the requisite conditions. Alternatively, the weekly values of the fuel ratio in terms of fuel used per ton of output can be plotted against the weekly output. Such curves give datum lines from which any improvement in method of operation or constructional alteration can be gauged and optimum rates of output assessed. A set of values for a reheating furnace is given in Table 10, from which it can be determined that a rate of fuel consumption of approximately 0.9 cwt. per hour is necessary to keep the furnace at its operation temperature, and to make good the heat losses in the furnace structure and the waste gases. The values in the last column show how the fuel ratio drops as the rate of output is raised.

TABLE 10. FUEL CONSUMPTION—OUTPUT RELATIONS
IN INTERMITTENT FURNACES

<i>Rate of fuel consumption cwt./hr.</i>	<i>Rate of output cwt./hr.</i>	<i>Fuel ratio : fuel (wt.) ÷ output (wt.)</i>
1.24	4.5	0.275
1.25	5.0	0.25
1.40	7.0	0.20
1.52	8.0	0.19
1.76	9.0	0.195

Figs. 17 and 18 illustrate the points referred to above and show the importance of furnace loading on furnace efficiency⁸.

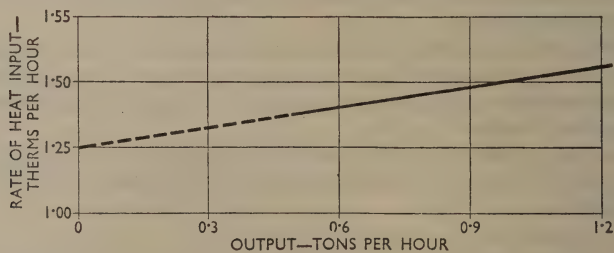


FIG. 17. Typical curve of rate of thermal input *versus* output for a continuous reheating furnace. The no-load losses are 1.25 therms per hour.

PRACTICAL HINTS TO OPERATORS

The following practical hints will be helpful to operators of various types of furnaces.

Coal-fired Furnaces

- (1) With hand-fired furnaces the depth of fire should be 15 inches. No fresh firing should exceed $1\frac{1}{2}$ -2 shovelfuls for each square foot of grate surface. Firing too heavily causes excessive smoke and waste of fuel.

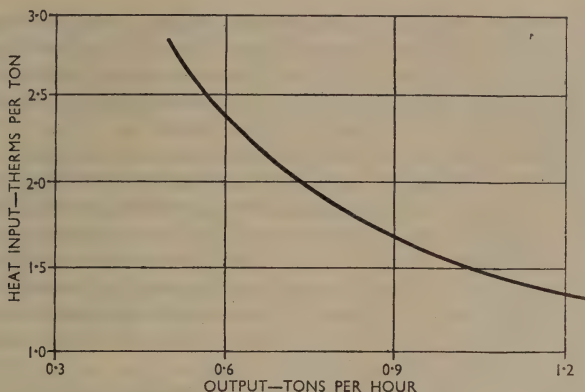


FIG. 18. Typical curve of rate of heat input per unit of output *versus* output for the case shown in FIG. 15.

- (2) Intervals between firing should be from 15 to 20 minutes in reheating furnaces, and should never exceed 30 minutes, even in heat treatment furnaces.
- (3) The grate should be kept covered, the fires level and free from holes, and the rake used when necessary.
- (4) Firebars must be evenly spaced, and burning or warping should be rectified at once.
- (5) Unnecessary wastage of cinders in the ashes is avoided by cleaning the fires carefully. After cleaning, the fire is worked back gradually.
- (6) The air supply is regulated to give bright clean fires.
- (7) Inleakage of air should be avoided, since it removes heat from the furnace and transfers it to the chimney. All sources of air inleakage should be patched up.
- (8) Dampers must be kept in good repair, and the draught in the furnace balanced to prevent either inleakage of air or blowing out of flame. In most furnaces a slight indraught below the door is consistent with balanced conditions of draught.

Whilst the above hints apply to hand-fired furnaces still operating it should be noted that mechanical firing is applicable to metallurgical furnaces. Furthermore, when properly operated, mechanical firing is much more efficient.

Coke-fired Furnaces

With coke firing, the larger the coke the thicker should be the fuel bed with a depth of 12–15 inches as a maximum. The conditions of firing differ from those of coal-fired furnaces, since no smoke can be produced from coke under any conditions, but guidance on all the other points is practically the same as for coal-fired furnaces.

Gas-fired and Pulverized-Coal-fired Furnaces (see also Chap. 12)

- (1) Burners should be kept clean and in good repair. All adjustable parts should move freely. Air controls on burner injectors often become jammed through dirt, corrosion or mechanical damage.
- (2) Dampers should be free, in good working order and not subject to inleakage of air.
- (3) The correct amount of air can be ascertained by inspection of the flame, though the indications will differ with various types of burner. More exact indication can be obtained by flue gas analysis, and it is of great help to furnace operators if a CO_2 recorder is installed for their guidance.

- (4) In blast burners which normally work with a non-luminous flame, a long lazy flame indicates too much gas. Correct combustion is obtained by shortening the flame until the yellowish colour just disappears. This is done by cutting down the gas, or increasing the air supply. The roar of the burner is then generally at its loudest.
- (5) In other types of burner, where mixing of gas and air is delayed, a bright yellow colour shows good combustion, the brighter the better.
- (6) Once the burners are set to give proper combustion individual burners should be adjusted as little as possible. The gas supply to the whole furnace should be reduced or increased whenever necessary by using the main valve only. As with coal-fired furnaces, inleakage of air should be avoided whether from furnace doors, open spy-holes or faulty brick-work. Air inleakage in effect transfers heat from the furnace to the chimney and is the cause of much waste.
- (7) In bogie furnaces the sand seals should be kept full.
- (8) The damper should be used to keep a balanced draught in the furnace. The correct position for the damper can be found by burning a small flame or blowing smoke into a sight-hole and adjusting the damper till the flame just flickers or the smoke just fails to be drawn into the furnaces.
- (9) Air slides and valves should be adjusted to correspond with the flow of gas. Whenever the amount of gas supplied to the furnace is altered the damper should be adjusted to re-establish the original pressure conditions within the combustion chamber or furnace.
- (10) Furnaces should not be lighted up until they are required, due allowance being made for the time necessary to attain working temperature. When furnaces are not required gas and air should be shut off and the dampers closed. The fuel supplied to a furnace should be correlated with the amount of work required by the furnace.

Oil-fired Furnaces (see also Chap. 13)

- (1) The liquid fuel at the point of use must be of right viscosity if the burners are to operate properly.
- (2) Water should be separated from the fuel oil; it can delay combustion and produce heavy smoke.
- (3) Burners should be fitted with graduated valves that permit a visual indication of the amount of oil which is being used; this permits ready adjustment of oil supply to load. Similarly, dampers should be graduated.
- (4) Burners should be dismantled and cleaned very frequently, preferably once a shift.
- (5) When the furnace is shut down, the burner should be removed to protect it from the radiant heat or protected by a metal sheet. The burner should not be kept cool by leaving the steam supply on.
- (6) The sizes of apertures in burners should be checked periodically.
- (7) The general principles of efficient operation that apply to other fuels also apply to oil-fired furnaces.

General Rules for the Economical Use of Fuel

- (1) With existing equipment, heat treatment must be planned so that as far as possible the appliance works at full load. Maintenance periods with no load and long periods of operation below capacity should be avoided. Major fuel economies can be achieved by careful load planning.
- (2) Flame should be kept within the furnace; gas should not be burnt beyond the furnace in the flue.

- (3) Doors should be reasonably well balanced and fit well ; they should be readily operated. Flames outside the doors cause warping or damage to the door lifting gear; the damage and loss become progressively greater.
- (4) Fuel should not be burned at full rate when heats have to be held.
- (5) A record should be kept of fuel used and weight of goods heated.
- (6) Leaky brickwork is one of the greatest sources of thermal loss. The furnace brickwork should be put into first-class repair so that infiltration of air cannot occur. It should also be painted with a suitable material, e.g. fireclay and cement or for lower temperatures a mixture of tar and fireclay, to prevent air leaking in through the pores of the bricks. Some excellent proprietary mixtures are now available for this purpose. Attention should be paid to the condition of the furnace doors, sight-holes, etc. Furnace doors should fit closely to the surrounding brickwork. The brickwork should be examined as a matter of routine at frequent intervals and in any event not less frequently than once a month.

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CHAPTER 20

FURNACES: CONSTRUCTION AND SPECIAL TYPES**INTRODUCTION**

THE principles of furnace operation and design have so far only been dealt with from the standpoint of the combustion of the fuel, heat transmission and the flow of gases. This chapter deals with the bearing of the structural features and the inferences from the heat balance on the problem of the efficient use of fuel in furnaces, and then with certain details of the operation of special types of furnaces.

Furnaces are classified on the following basis:

- I. Melting furnaces, including hearth, crucible and shaft types.
- II. Sintering furnaces, represented as a typical example by the cement kiln.
- III. Kilns and ovens.
- IV. Furnaces used in the glass industry.
- V. Reheating furnaces.
- VI. Heat treatment furnaces.

STRUCTURAL FEATURES**STRENGTH AND DURABILITY OF FURNACES**

The methods and materials used in furnace construction have an important bearing on fuel efficiency since breakdowns and delays may be a source of heat waste. Refractories and insulation are dealt with in Chapter 23.

The design of the structural framework of the furnace is based on the well-known principles of mechanical construction. A special point in its bearing on fuel efficiency is that robustness is essential, since repeated heating and cooling of structural members together with the concomitant expansion and contraction of the refractory materials used can, in course of time, induce a remarkable degree of distortion of framework. Large furnaces of insufficient robustness have been known to be several feet out of alignment after long use where sufficient strength and allowance for expansion have not been applied. Then cracks in brickwork develop more readily, causing air inleakage or flame emission, and a lowering of furnace efficiency. Cast iron plates and structural steelwork are not, in general, satisfactory for the construction of parts exposed to high temperatures, for which special materials such as heat-resisting alloys must be used. The development of these materials during recent years has resulted in considerable progress in the mechanization of furnace practice, and the provision of structures and mechanisms able to withstand the internal heat of the furnace. Such materials are used extensively up to about 1,000° C. and for special work at even higher temperatures.

They must be resistant to scaling, and have sufficient hot strength to permit of their use in many types of mechanisms such as conveyors. The factor on which selection of the material is based in regard to this last-named property is known as the *creep strength*, the load which the metal can carry for long periods at the temperature involved without perceptible creep. Other important properties are resistance to carburization (carburizing boxes), to the effects of repeated heating and cooling (chain conveyors, particularly those immersed in quenching media), heat diffusivity (glass furnaces), malleability (for bars and sheets), machinability.

THE FURNACE CHAMBER AND ROOFS

Provided the abutment of the arch, or skewback, is adequately supported by a strong framework with tie rods, the arch must rise on heating. In selecting brickwork the expansion characteristics of the refractory to be used must be known, also whether there is any after-contraction on firing to the temperature at which the roof is to be operated. If the brickwork were incompressible then with good shaped material, the bricks would be in contact over their full length near the arch support, but near the crown of the arch they would tend to touch only at the inner edge. Roofs are constructed of specially shaped end bricks abutting on the skewback to allow for this variation to be corrected by natural expansion during heating. Actually, all firebricks are capable of crushing elastically to a degree compatible with a robust construction, and, in general, a rigidly bricked roof gives satisfactory service provided ample rise in the arch is allowed for (e.g. $1\frac{1}{2}$ inches to the foot). Further, the softening of the bricks at furnace temperatures and the lower refractoriness resulting from the application of pressure, permit plastic compression of the bricks on the furnace side of the arch, and tend to equalise the load and compensate for irregularities of shape. The line of thrust of a hot arch departs farther from the median line of the brickwork towards the hot surface as the centre of the span is approached, so that the greatest deformation is likely to occur where the initial separation of the brickwork is greatest.

Furnace roofs fail either by yielding of the skewbacks, or by spalling and wear. Spalling can weaken an arch, and it can then finally be reduced to a condition of collapse through normal slag attack and erosion by furnace gases and fume. A roof can become remarkably thin through wear without collapse provided the abutments are rigid, but then the question of heat loss by conduction and from external surfaces possibly outweighs the loss of durability of the roof, unless (as so frequently occurs in industrial practice) it is necessary to wait for a convenient period for repair. It may be urged with good reason that planned maintenance, requiring repairs to be done at specified intervals, is preferable to the policy of striving for the absolute limit of durability.

Under suitable conditions abutments can be made rigid and dependence can be placed on the rise of the arch; alternatively, spring loaded or adjustable tie rods may be used, but these latter require skill in adjustment, and unskilled handling may result in failure of the arch.

Distances greater than 18 feet are seldom spanned by a single arch. They are either broken up into several smaller spans, supported on skewbacks, carried on longitudinal girder reinforcement, or slung from overhead beams. Flat roofs, built of refractory tiles suspended by hangers from overhead girders are also used. The relative merits of the sprung arch and the suspended roof depend entirely upon the conditions, the occurrence of movement (as in soaking pit lids) being a factor of significance operating against the success of the flat roof. A complicated shape constructed in fired refractory material is always more vulnerable to the effects of variable stresses than the simple shapes that can be used in an arched roof. On the other hand, under suitable conditions of use the suspended roof may be preferred since it eliminates the need for the skewback and gives freedom of design in the sidewalls for the provision of openings to the furnace chamber.

Roofs 9 inches thick are generally insulated with advantage, except in special cases over combustion chambers where the temperature conditions are too severe for the brickwork. Selection of a better-class refractory brick may, on the other hand, be successful in such a case.

Roofs may collapse from mechanical injuries caused by explosions or impacts. The best brickwork and design are of no avail against destructive

treatment that may result from errors in lighting up or in controlling charging operations.

In roof construction attention should be devoted to the choice of brick shapes to give uniform stresses, and a reasonable gas tightness to obviate the excessive leakage of hot gases which occurs in a badly built roof due to the buoyancy of the hot gas. In certain types of kilns it is considered good practice that the crown or arch should spring from a wall behind the kiln lining. The construction of crowns of certain types of kiln is not dealt with in this book.

SIDE WALLS AND HEARTHES

If the side wall forms the support for the roof its correct construction is of primary importance in relation both to the thrust of the roof and to that of the hearth. The major fault to be avoided in the construction of the lower part of the furnace lining is a lack of adequate strength for the supporting girders of the hearth, which should be securely anchored to the buckstays. In high temperature furnaces side-wall support should be provided by the use of strong cast-iron plates, particularly in situations not required to be made accessible for the purpose of brickwork repair. Such construction admits of the ready use of the highest grade insulating bricks in side walls.

Adequate insulation of hearths in modern furnace practice is imperative, and it is practicable to obtain material capable of withstanding the heaviest hearth loads. Economical furnace operation depends to a considerable degree on the manner in which uniformity of temperature is rapidly attained. Since, except in under-fired furnaces, the hearth is the coldest part of the furnace, provision for its adequate heating is a prime factor in good furnace design. At the same time adequate refractoriness, stability and resistance to attrition must be provided.

It is not good practice to incorporate an excessive amount of brickwork. There must be the correct combination of suitable refractories to maintain thermal insulation and mechanical stability. Stability is assisted by ventilation; the most satisfactory hearth is mechanically supported and air-cooled from below.

Slagging troubles or soft hearths can usually be remedied by a correct selection of refractories, for example, by the use of a superior firebrick or a basic refractory such as dolomite, chromite, or in special cases magnesite, and sillimanite, carbon or carborundum. In siliceous hearths slag is run off in liquid form through a tap hole, and the condition of the hearth is made good by fettling with a suitable refractory as, for example, sand or iron oxide cinder when the slags are ferruginous. Dry hearths should always be kept clean and free from scale and cinder by raking at convenient intervals of time.

FOUNDATIONS

The design of the foundations is not a feature that can be usefully discussed as a factor entering into the problem of correct practice in normal operation, since it is a feature of the initial construction. Overheated foundations may, however, be the cause of uneconomical operation by permitting subsidence which gives rise to cracks in brickwork, and resultant wasteful inleakage of cold air. Thin, non-ventilated, brickwork hearths which are, however, capable of being readily altered, can cause overheating of concrete, dehydration of which begins at 260°C . and is completed at 480°C . Limiting thicknesses are $D/6$ for furnaces working at below $1,205^{\circ}\text{C}$. and $D/8$ for 870°C ., D being the shortest dimension of the hearth in feet.

HEARTH SUPPORTS, SKIDS AND HANGERS

A wide range of mechanical devices is used for the purpose of hearth supports, skids and hangers, to enable stock to be moved readily through continuous

furnaces. From the standpoint of fuel efficiency certain general principles should be observed in their construction and maintenance.

Apart from waste of fuel and output due to interrupted campaigns and the preservation of general economy of operation, excessive heat losses may result from water cooling, but its use under certain circumstances is inevitable. Skid pipes are usually of hydraulic section, and must be securely anchored in the furnace hearths. They may be fastened into the anchorage in such a manner as to admit of being turned to expose new and unworn surfaces for further service or, alternatively, welded strips may be used to take the wear. Safeguarding the water supply and preventing blockages in pipes are obvious precautions.

The main objection to the use of water cooling in skids arises from cold patches in the stock; finishing periods of heating must then be made by transfer to solid refractory hearths. The use of dry skids, hearth plates, and mechanical conveyors introduces a field of furnace practice of a specialised type. Where mechanical conveyors are used the amount of sensible heat lost from them may be an important item in the heat balance. The heat-resisting steels already mentioned are frequently used for these purposes.

JAMBS, DOORS AND OPENINGS IN SIDE WALLS

Openings in side walls can be a cause of inefficiency, particularly in furnaces operating at temperatures above $1,000^{\circ}\text{C}$. Open doors lose heat at a very high rate from direct radiation to the atmosphere. Distorted buckstays, piers and jamb reinforcement cause air inleakage, and flame loss, for proper fitting of doors is no longer possible. Modern refractory practice in the provision of high temperature insulating materials, on the other hand, makes practicable more robust and better doors. A most important feature of furnace practice is attention to the sealing of the doors to prevent such leakages. The main factors in overcoming such disabilities are the initial robustness of the reinforcement and the use of well-fitting door frames, side plates and steady mechanical action during movement. Water-cooled doors may be essential, but the heat losses due to the cooling action should always be examined in relation to the general economy.

A badly fitting discharge door on a reheating furnace having a gap 1 inch wide and 24 inches long along its top edge will give a heat loss of approximately 200,000 B.t.u. an hour due to escaping gases if the furnace is operating at $1,100^{\circ}\text{C}$. with an exhaust temperature of 700°C ., and with a normal furnace pressure. This clearly shows the loss which can be obtained from a comparatively small opening.

AUXILIARY PLANT

In addition to the furnace proper there is often much ancillary equipment that requires attention if the best results are to be obtained.

DAMPERS

The function of a damper is to regulate the draught; accordingly it becomes a prime instrument of the furnace economy. The controls should always be situated in such a position as to be readily accessible, and preferably also permit of sighting the flame when adjustments are being made. The choice of the material from which the damper is made depends on the conditions of operation. It must not crack or warp, nor must brickwork become dislodged. It should move easily in its seating and be readily capable of fine adjustment since quite a small movement may mean a waste of many tons of fuel. Allowance should be made for expansion, and suitable covers or leakage seals provided to prevent the inflow of cold air to the flue. If the furnace is temporarily shut

down the damper should always be closed. Closing the damper when shutting down the furnace is equivalent to turning off the fuel valves since it prevents cold air inleakage.

Water-cooled dampers of special design or dampers constructed of heat-resisting alloys are necessary for the highest temperatures. For gas-tightness they should be made to slide on inclined damper frames machined on the working face.

FANS

Controlled draught, whether forced, induced, or balanced (Chaps. 8 and 11) assists the maintenance of the correct air-fuel ratio, and the adjustment of the rate of heat input to the most economical value. Mechanical draught is generally indispensable with recuperators, which require high velocities of air flow for adequate efficiency, with consequent increase of resistance.

Fan design and selection are matters for the specialist. The principal consideration when fans are installed is to see that they are maintained efficiently by regular lubrication and cleaning. Particular care should be paid to the inlet side of the fan and suitable protection placed to prevent foreign matter from being drawn into working parts. With induced draught fans serious damage may result from flame impingement on the blades or overheating from other causes. Valves and dampers in the fan circuit should be readily controllable. A fan gives a ready means of registering the air flow to the furnace either by pipe attachment with orifice gauge placed at the air inlet or by the use of an orifice gauge in the supply main. Care should be taken to ensure that the character of the flow in the main is suitable for accurate measurement if this method is used. Straightening grids may be used in difficult conditions to prevent swirl effects.

CONTROL VALVES

Control valves regulate the amount of fuel entering the furnace. For every furnace there is an ideal rate of consumption of fuel for the particular heating operation. Any departure from the correct setting of the valve results in loss of efficiency. In intermittent furnaces there is reached a moment at which the soaking stage is being approached, and the rate of heat input must be reduced. It is accordingly imperative that control valves should be provided with suitable indicators, for example quadrants and pointers, to show the exact setting of the valve. All valves should be examined, cleaned and adjusted regularly to ensure that they are in good working order.

BURNERS

The accurate distribution of temperature is a matter of importance, frequently calling for the use of gaseous and liquid fuels of all types. The burner construction is accordingly a critical feature of the furnace design.

The main distinction of the various types of burners in common use lies in the method of aeration used. The intensity of heating and the form of the flame are governed by the nature of the fuel, but for any given fuel the nature of the flame and the character of the heat release are controlled by the manner in which the combustible and the air are brought together. The flow characteristics of the two streams depend on the laws of flow of fluids, but in the flame a complex system of changes may be brought about, and knowledge of the circumstances affecting the heat release is so far more or less empirical.

Natural Draught Burner. This type is essentially an injector burner of the bunsen type, the gas being slightly above, and the air at, atmospheric pressure. A proportion of the air is entrained with the gas as primary air, the remainder being induced by the furnace draught as secondary air.

Pre-heated Air Burners. This type takes the form of one or more ports, and is supplied with pre-heated air from a heat recovery appliance, a recuperator or regenerator. It is generally used on large furnaces. Burner controls may consist of slide dampers built into ducts in both the air and gas supply systems. The gas is delivered at low pressure, and the air either by natural draught or at low pressure after passage through the preheater. The method of draughting the furnace and of controlling the waste gas dampers has a material influence on the nature of the flame.

Low Pressure Blast Burners. With these burners the gaseous fuel is supplied at pressures between 2 in. and 8 in. w.g., and with air pressures varying from a few inches to 5 or 6 lb. per square inch. They may be used with either cold or pre-heated air or both. They constitute the most simple and general type. The gas and air supplies are generally separately controlled, and it is advisable to ensure that the control valves are fitted with suitable quadrants and indicators to assist in the correct setting of the valves. They are normally fitted into a cone-shaped refractory burner block, which serves the multiple purpose of assisting the flow of gases to give the correct form to the flame, assisting ignition at lighting up, and maintaining combustion by the proximity of a hot radiating surface. With a refractory burner throat the relatively cold flame of a low grade fuel is not so readily blown off the burner. Maintenance of the correct gas-air ratio may be assisted by coupling the air and gas valves together through a proportioning mechanism, but it is essential to have good pressure regulation, as by pressure governor on the fuel gas. Turbulence and good mixing are assisted by providing deflecting vanes in the annular throat carrying the air to give a vortex motion to the gases.

Crude gas is burnt in both of the above types of burners, but ample capacity must be allowed in the gas passages and valves, where tarry deposits may accumulate and cause stoppages. With hot gas, good insulation of gas supply mains is essential to keep tarry constituents as far as possible volatile, and provision should be made for the draining away of the tar without interruption of operation. Adequate cleaning gates, requiring the minimum of time for clearing deposits, are necessary. Bends should give good streamlining and mixing devices and nozzles should not be used inside the burner. Gas and air should have an ample mixing space. Disc-type valves are preferable for use with gases likely to contain tarry or dusty constituents.

This type of burner readily permits adjustability of flame length by admitting the air in separate supplies, an inner and an outer stream supplied in an axial direction.

The so-called *diffusion burners* fall into this class. In these the gas and air are made to diffuse slowly into one another, whereby mixing is gradual and the maximum length of flame attained. The ports may be annular, one within the other, when the flame is circular, or they may be long slots producing a flat stream of flame. They are particularly suitable for plate heating when operating on mixed gas.

It is frequently overlooked that air pre-heat changes the character of the flame, and that where the temperature of pre-heat is varying a specific setting of a flame cannot be maintained because the air is constantly changing in volume. Accordingly, burners utilizing pre-heated air should be good mixing burners.

High Pressure Gas Burners. This type of burner may be operated in between one and three stages of injection according to the class of fuel and conditions of use. Gas pressures may be from 1 to 10 lb. per square inch. Alternatively, a similar type of burner may be operated by means of pressure air used as an injector to entrain gas supplied at low pressure.

With the high pressure burner fans are not required, distribution mains are reduced in size, and steady pressures can generally be maintained by the use of a reducing valve as governor, though successful installations are operated without a governor. This system is convenient for use in converting existing furnaces to gas firing where space is limited, and only the simplest attachment to the furnace structure is permissible. With the elimination of air pipes and fans the risk of explosion is eliminated. The burner, however, lacks flexibility. The air/gas ratio is influenced by the pressure in the furnace and the output of the burner, and the more these factors vary the greater the departure from ideal combustion conditions. To avoid backfiring the lower limit of output is about $\frac{1}{2}$ to $\frac{1}{3}$ of full load, so that the burner is not suitable for furnaces requiring to be operated in a wide range of temperature—as, for example, some types of tempering furnace. The pressure of gas required to be available in the burner is less with the lower grade gases on account of the higher gas/air ratio, the required pressure usually being:

	<i>Calorific value :</i> <i>gross)</i> <i>B.t.u./cu. ft.</i>	<i>Pressure :</i> <i>in w g.</i>
For coke oven and town gas	500–550	118–196
Mixed gas (coke oven and blast furnace)	200–240	59–118
Producer gas	150	39–59
Blast furnace gas	95	20–39

Single-stage induction can be applied up to the point at which the air requirements of the gas do not exceed 2.3 times the gas quantity. The gases of lower calorific value have a lower gas pressure at which the flame flashes back in the burner, and the lower limit of capacity lies between 25 and 50 per cent. of the highest load according to the type of fuel gas and the furnace temperature. Since coke oven gas and town gas require more than 2.3 times their volume of air two-stage induction is generally applied when burning these gases.

Pre-mixing Burners. This is a popular type of burner which admits of the gas and air being delivered to the throat ready mixed. It has the advantage that the combustible mixture can be distributed by suitable mains to a number of different points in the furnace to produce the required temperature distribution. The aeration of the gas is effected in an injector mixer by the use of high pressure air, the gas pressure being stabilized by the use of a governor. This burner is suitable for a very uniform furnace atmosphere, steady heating conditions and a well distributed supply of heat. Alternatively, high pressure gas can be used to induce air.

The velocity of the gas in the distributing mains must be above the velocity of flame propagation, and at the burner inlets to the furnace cooling fins are used to safeguard against backfiring. The arrangement is unsuitable for high degrees of preheat of gas or air. The safe limiting temperature of air preheat is 300° C., though it has been claimed to be practicable up to 500° C.

With gases of low calorific value there is a greater tendency for the flame under normal operating conditions to be blown off the nozzle of the burner. These burners have the advantage of simplifying control from the standpoint of the operative. They are readily adaptable to automatic regulation of furnace temperature.

The principle of pre-mixing may also be combined with the use of secondary air at the burner nozzle, either supplied by means of a fan or induced by the draught of the furnace. The use of secondary or tertiary air can be applied in this manner to any type of injector burner. It is readily applied with high calorific value gas because the mixture ratios with such a fuel are appropriate and far above the upper explosive limit, but as each additional stage of air admission is made there follows the attendant loss of simplicity of control.

Combustion in Films and Surface Combustion Burners. Finally, there are the multi-jet burners in which the gas and air are subdivided into a number of small streams, producing in effect a series of films of flame. The flame volume is controlled, and burning of stock obviated. Excessive local temperature in the body of the flame is also avoided.

The modern burner is virtually a multi-holed brick, the refractory surface of which becomes highly heated and so forms an effective radiator. In the latest type the surface of the refractory is formed in the shape of a hemispherical cavity which serves as a concave reflector of radiation and accordingly is a very efficient heating appliance. The ultimate result of the combustion of gases in contact with refractory surfaces is the production of flameless incandescent surface combustion. Air preheating is practicable. The brickwork of which the burner is made must be of high quality refractory, fashioned with a high degree of workmanship. In certain applications the need for a high standard of maintenance may be a disadvantage.

Rules of Practice for Burner Operation. It is an important feature of all burner efficiency that certain simple rules of practice should be observed in their operation. For brevity they are summarised as follows:

(i) Correct setting of the gas and air valves, and the adjustment of the damper to give balanced draught in the furnace is the first golden rule. These settings should be marked on appropriate quadrants.

(ii) Where several burners are operated from one rail the valves on each should be adjusted to give correct heat distribution and the main gas and air rates are controlled on main valves and dampers.

(iii) The installation must be operated at the correct pressures. Pressure gauges should be used.

(iv) Good maintenance comprises adequate cleaning, changing of corroded or damaged jets, free valves, concentric jets or burner throats, correct seating of the burner throat in the refractory port.

(v) Governors, proportioning apparatus and valves should not be so placed as to become overheated.

(vi) All instruments are to be kept clean and in good order. Makers' rules should be observed.

CONTROL OF FURNACE ATMOSPHERE

In furnace operations the maintenance of a specific type of furnace atmosphere is frequently essential in order to avoid oxidation of the stock or to preserve a surface condition (see Chapter 19). In the more special operation such as bright annealing the material may be heated out of contact with the products of combustion, and controlled atmosphere provided by means of an auxiliary appliance. The type of atmosphere used depends upon the class of material heated and the operation involved. The matter is one for special study since in the reactions involved many complicated equilibria must be considered.

For maintaining a constant furnace atmosphere with varying rates of fuel supply a constant fuel/air ratio is generally necessary. The commonest method of adjusting the furnace atmosphere, is that of visual inspection. With some fuels the decision is relatively easy; a so-called reducing atmosphere is smoky and a haze may be apparent; a neutral or oxidizing atmosphere is clear. With clean gaseous fuels, coke oven gas, water gas or clean producer gas, these indications are absent. With certain types of burner the brightness of the flame is a guide, but in the absence of any positive means of controlling the fuel and air flow resort must generally be made to gas analysis.

With gaseous fuels the use of automatic proportioning equipment is the simplest and the most reliable method of control. Mechanical interconnection

of gas and air supply is practised, but is not infallible, since with variations of gas and air pressure, fuel quality and furnace draughting the settings of the valves may readily be thrown entirely wrong. Other devices used are:

(i) Proportional mixers, operated by a positive blower, a fan or a jet, working in conjunction with a gas governor to maintain constant pressure of gas supply. A rich mixture is induced through adjustable ports and secondary air is induced at the burner nozzle. In another type an inspirating Venturi tube acts both as pump and proportioning device. Either gas or air under pressure may serve as the power medium.

(ii) Gas/air controls, applied by means of flow orifices. The flow of gas and air is measured by means of orifice gauges. The pressure head across the gauge is proportional to the square of the velocity of flow for fluids of low viscosity. The pressure drop through the two orifices by acting on a balanced system of diaphragms or floats sets up a pressure differential, which operates a relay either one way or the other to operate the power unit. The power unit operates the control valve governing the variable flow. By setting the differential mechanism by a convenient device the gas/air ratio can be adjusted to any desired value.

LABOUR-SAVING APPLIANCES

In modern furnaces many new types of mechanical appliances are now becoming an essential feature of the furnace operation, including charging machines, mechanical stokers and the driving mechanism for rotating hearths. Charging machines should be flexible, easily controlled, simple to adjust and quick in their action. In the use of conveyors, temperature must be controlled within specified limits to avoid destruction by overheating. With moving hearths sand seals must be always kept properly filled with suitable material; otherwise damage to bogie carriage side plates and wheels or serious inleakages of cold air may occur. Foreign matter must not be allowed to drop into the seal to cause excessive friction or dislodgment of brickwork.

IMPROVEMENT OF EFFICIENCY AT FURNACE REBUILDS

In the course of investigations into conditions of operation it may become apparent that improvement can be effected by rebuilding or structural change in the furnace. Since the science of furnace heating involves many complex factors, it is desirable to take the advice of a furnace expert on structural changes.

Attention should be paid to the maintenance of mechanism and furnace brickwork. The cleaning of flues, repair of dampers, maintaining the cleanliness of heat exchange surfaces as in recuperators, and the sealing of cracks in brickwork, all have an important influence on the amount of fuel consumed. An unsuitable size of grate, a furnace too large because it has been built for over-size material rarely handled, crowns too high or too low, flues of insufficient capacity or defective design, unnecessary burners, wrongly disposed and dimensioned ports, fans of an uneconomical capacity, unsuitably dimensioned combustion chambers, insufficient lagging of doors and furnace structure can be corrected during the course of normal maintenance. Many of these defects are to be found even in modern furnaces because users are still disposed to look only at first cost. A robust, well-built and insulated furnace is always the cheapest in the long run.

INSTRUCTION BOOKS

Finally, in furnace or kiln operation, there should be compiled at the installation of the plant a handbook of guidance to the plant operators and engineers, in which should be specifically stated the essential "rules of practice" for

operating the plant, and the points to be watched in maintaining the plant in good order. Such handbooks are now prepared by the best constructors and, if consistently used by the operators, are most valuable instruments in ensuring efficient practice. They should be adequately illustrated by simple sketches, and expressed in brief and direct terms. Much of the material contained in Fuel Efficiency Bulletin No. 43, although subject to modification in detail since its publication¹, will still be found valuable to furnace operators.

FURNACE TESTING

A number of British Standard Specifications have now been prepared for assessing the performance of various types of furnace. These give guidance as to the technique to be employed for the measurement of fuel consumption, throughput and heat losses. The methods to be employed for the determination of the heat balance are indicated. The interpretation of the results, however, is quite another matter.

INFERENCES FROM THE HEAT BALANCE

The normal method of control of heating furnaces is based on the use of graphs of fuel consumption and rate of output. (See Chapter 26.) In order, however, to establish improved practice by modification of the furnace operation or design details, analysis of the heat balance is necessary.

Since heat supplied = useful heat + structure loss + exhaust gas loss, it is apparent that for a constant fuel consumption and a constant structure loss an increase of useful heat can take place only by reduction of the exhaust gas loss. The value of a knowledge of the temperature and composition of the gases leaving the furnace accordingly becomes apparent.

In batch or intermittent furnaces, since the temperature of the furnace passes through a cyclical change both the structure loss and the exhaust gas loss vary. There are also external heat losses (Chapter 9) and losses due to the storage of heat in the brickwork.

Structure loss.

The structure losses become more important the higher the furnace temperature, and heat protection is then all the more necessary. Whether inner linings can be replaced by hot-face insulation, or first quality brickwork insulated by standard external insulation is mainly a question of temperature, and amount of wear and attrition imposed by the process on refractories. Furnace crowns over fireboxes operating reheating furnaces cannot be insulated unless high-grade refractories are used. Insulation may only result in uneconomical refractory wear since the mean temperature of the inner lining is raised by the use of the external insulation. In pulverized fuel firing the reaction between possibly molten ash and refractory material imposes a limitation on the method of building. Expedients to overcome disabilities of this kind include the provision of patched linings of dolomite, magnesite or siliceous materials in combustion chambers, and the construction of flue off-takes of ample size and accessibility to remove accretions of ash and clinker.

In interpreting the characteristics of the refractory it should be borne in mind that the safe limit of under-load refractoriness is in general 100 deg. C. lower than the value shown by the normal laboratory test, since at high temperatures refractories tend to behave as semi-viscous bodies, and with the passage of time tend to flow, so that the structure may collapse. Alternatively a greater thickness of refractory brick may be used which will reduce conduction loss and at the same time give greater stability to the structure. This technique applies in the use of both suspended and arched crowns. In this

connection the importance of the hot-face insulating refractory materials now available must be emphasized.

Artificial cooling by means of water as in jambs and partition walls or by compressed air leads to substantial losses. Compressed air is nearly always a wasteful and expensive means of controlling the flow of heat. The temperature of the external surface of a $4\frac{1}{2}$ inches firebrick wall can be reduced from 400°C . to 40°C . by means of a jet of compressed air, and the temperature gradient through the wall when it is maintained at a temperature of $1,400^{\circ}\text{C}$. accordingly increased from $1,000^{\circ}\text{C}$. to $1,360^{\circ}\text{C}$., thereby causing an increase of 36 per cent. in the heat transfer.

The storage loss is discussed in Chapters 19 and 23. This loss and the wall loss by conduction are complementary for the lower the storage loss brought about by reducing the thickness of the wall the greater the conduction loss. The relative merits of each case must depend upon the period of the heating cycle, whether the heat stored has time to penetrate the wall before the heating operation is completed. To determine when the loss by conduction overtakes the loss by storage it is noted that equilibrium of heat conduction begins to occur when $L^2/4Dt$ approaches 0.4,

where L = thickness of the wall (metres)

t = time since the beginning of the alteration in temperature (hours)

D = thermal diffusivity (sq. metres per hour).

Exhaust Gas Loss

In all furnaces the use of the continuous principle is conducive to a low exhaust gas temperature, but in batch furnaces the gas must leave the furnace at a temperature above that of the stock. Particular care must accordingly be taken to obviate air in leakage. How far this temperature must be above the temperature of the furnace depends upon the character of the heat transfer from the gases. The governing factor in this type of furnace is radiation from the heating gases and the structural re-radiation, which outweighs the influence of convection. (See Chapter 9.) Gas radiation depends on the composition of the gas but even more on the thickness of the gas layer and the temperature. Since the temperature is fixed by the operating conditions it must be in the interests of the furnace economy that there shall be within it large radiating masses of gas. This involves the use of relatively large furnace chamber capacity, provided that such provision is not at the same time outweighed by an increased structure and external surface loss, and that the flow pattern of the hot gas below the roof does not give a cold layer of air adjacent to the charge. Further opaque currents of partially burnt gas may form an insulating layer since it may be impenetrable to the dark heat rays of the hotter gas above. Accordingly the expedient of raising the crown of a furnace to give a better radiating gas layer and an increased surface of direct wall radiation will fail if care is not at the same time taken to ensure complete gas circulation and prevent air infiltration. A ribbed roof construction to create turbulence, as well as to increase heating surface, is a beneficial form of construction in this respect. Auxiliary burners and turbulent admission of secondary air are also expedients used to effect the same advantages.

Heat transmission co-efficients in industrial furnaces of the continuous pusher type vary from 50 to 20 B.t.u./sq. ft. hr. deg. F. at $2,200^{\circ}\text{F}$. and $1,480^{\circ}\text{F}$. respectively*, for gas layers about 1 ft. 6 in. thick. Since radiant heat transfer depends on the fourth power of the gas temperature, there is

* Approx. metric equivalents: 250 kcal./m²/h/deg. C. at $1,200^{\circ}\text{C}$. to 100 at 800°C .

an economic limit to the length of continuous furnaces beyond which the heat transfer becomes too slow as the gas temperature falls. At this point it may pay to divert the gas through a metallic recuperator in order to pre-heat the air for combustion; here convection transfer under conditions of forced circulation gives better utilization of the heating surface.

From this discussion of the heat balance it will be seen that fuel efficiency is promoted by the following:

- (i) provision of adequate heating surface.
- (ii) adequate space for combustion and the heating gas currents.
- (iii) prevention of cold gas layers by means of auxiliary apparatus for creating turbulence.
- (iv) prevention of infiltration of air by making the furnace as gastight as possible and by control of draught.
- (v) a critical rate of throughput of material to be heated which is determined by the point at which the combined loss due to the structure absorption and the sensible heat in the exhaust gases is at a minimum.

Exhaust Gas Loss by Unburnt Combustible Matter

It has already been shown that unburnt combustible matter can cause serious loss of furnace efficiency. Thus in the combustion of blast furnace gas 5 per cent. CO plus 1 per cent of H_2 in the waste gases is equivalent to a loss of 25 per cent. of the potential heat of the gas, and 1 per cent. of CO is equivalent to a rise of about 90 deg. C. in the flue gas temperature.

Combustion control can be assisted by the use of secondary and tertiary air introduced at positions in the flow of the gas stream, provided that the change is not endangered by excess air or a flame too strongly reducing. The same effect can be attained by auxiliary burners carrying the needed excess of air. Other effective measures are the use of air/gas controls.

For certain types of operation where low temperatures and temperature uniformity are required long flames are used involving slow diffusion of volatile combustible and air. These are the most difficult to control and without late additional air admission may cause local overheating.

Losses unaccounted for

In the heat balance sheet there is always an item to cover the unascertained losses not readily measured, and the balance of error in making the determination of each specific loss. These include:

- (i) losses in foundations.
- (ii) gas leakage.
- (iii) losses from open doors.

(i) *Losses in Foundations.* The loss in foundations is a somewhat special study. J. D. Keller,² who showed that the total flow of heat through hearths of a given shape is proportional not to the area, but only to the diameter or width. The conception of an equivalent thickness of hearth was taken to be that thickness of a wall of the same material, through which the rate of flow of heat would be just the same as the actual rate through the hearth if one surface were held at the temperature of the interior of the furnace, and the other at the temperature of the surrounding air.

In unventilated hearths the equivalent thickness of the hearth at its centre was found to be slightly more than half the least width of the hearth. The average equivalent thickness referred to the whole area of the hearth was one-quarter the hearth diameter for circular furnaces, $22\frac{1}{2}$ per cent. of the width for square hearths, and its value increased as the ratio of the lengths of the sides of rectangular furnaces, approaching a limiting value of 27 per cent. of the least width for very long hearths.

Mathematical techniques have been developed for determining the temperature penetration into the ground. From them can be deduced the continuous nature of the heat saturation, which can lead to failure of foundations, the risk of which is not entirely eradicated by insulation. Insulation only delays the heat penetration; it does not stop it. Accordingly high temperature furnace hearths should always be ventilated.

(ii) *Gas Leakage*, and (iii) *Losses from Open Doors*. In reheating furnaces the gas pressure difference produced in a column of hot gas due to its buoyancy as against the same height of the outer atmosphere amounts to approximately 0.012 inch w.g. per foot height (1 millimetre w.g. per metre). If the gas pressure at the sill level is to be zero, and no air be allowed to be drawn in, this buoyancy of hot gas must accordingly produce a positive pressure at the top of a furnace door. Alternatively, to balance the draught to give zero pressure at the top of the door is equivalent to carrying a negative pressure, that is an indraught, at the sill level. Thus, when the door is opened either an indraught of cold air or an outblast of hot gas results. Generally both occur.

Further reference to the magnitude of the radiation loss from hot surfaces (Chapter 9) permits an estimate to be made of the direct heat loss derived from this source. Accordingly the heat losses due to the repeated opening of furnace doors may be considerable, and attention to this phase of the operation is imperative (Chapter 19). The importance of gastightness and correct balancing of the draught is again apparent.

Specific types of furnace are now considered.

I. MELTING FURNACES

Melting furnaces may be of hearth, crucible or shaft type. The technique of operation invariably depends upon special technical considerations, peculiar to each process, and frequently these have an over-riding influence on the manner in which the melting operation is conducted. It is therefore only possible here to review those features which are common to melting furnaces as a class.

Hearth and crucible furnaces for those processes requiring the highest temperatures, for instance steel making and glass manufacture, are frequently combined with regenerators or recuperators. In shaft furnaces the fuel is mixed with the charge, and the air for combustion blown in at tuyères.

Apart from problems of mechanical design, economical performance depends upon three major features:

(i) The design of the melting chamber, its shape and dimensions in relation to the rate of melting desired, and a critical rate of heat input up to the limit at which the refractories are able to maintain the mechanical stability of the furnace. Accordingly, the search for economy must be made by the study of the dimensions in relation to the rate of output required, and determinations of the critical rates of heating necessary for each set of conditions ruling. This means that importance must be attached to surveys of draught conditions and methods of firing.

(ii) Efficient combustion is of paramount importance since high rates of melting require the maintenance of certain flame temperatures, and whether conditions are satisfactory or not may depend upon a relatively small temperature gradient between the flame and the material heated. Accordingly, preheat of fuel and air becomes critical, and regenerative or recuperative methods must be efficiently applied. Suitable port or burner design and the correct disposition of the stream of hot gases in the working chamber may become equally essential.

(iii) Process factors, of particular importance in steel making and metallurgical melting generally, which may introduce the over-riding factors referred to above, are outside the present compass of the discussion.

In general in hearth and crucible furnaces a fundamental relationship exists between the rate of fuel input and the rate of melting for any particular class of furnace. The exact nature of this relationship depends upon a multitude of factors, including the furnace design and that of its auxiliaries as well as

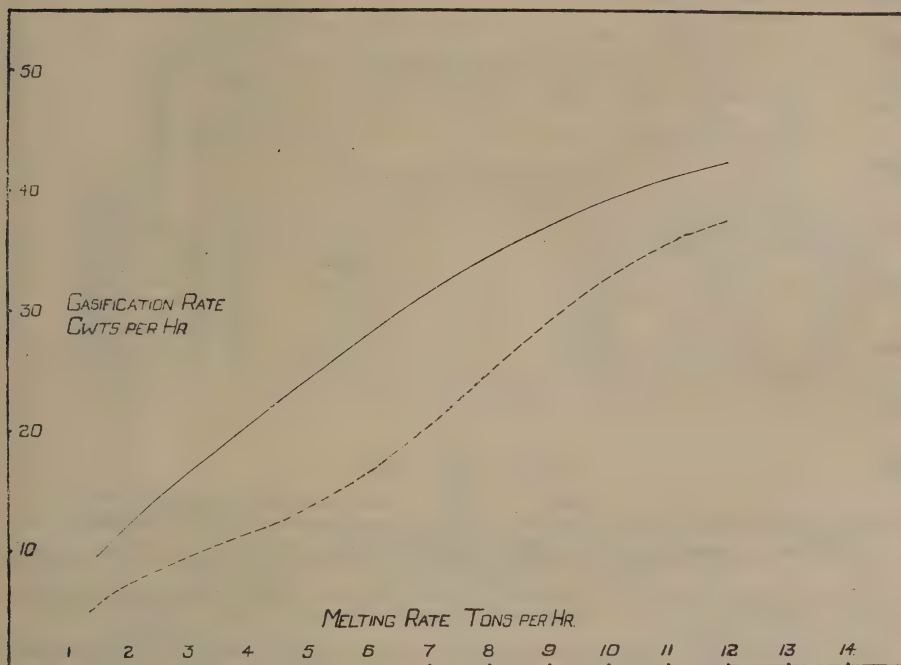


FIG. 1. Relation between rate of fuel consumption and rate of smelting in open hearth furnaces. The band between the curves shows the region in which results have been recorded.

(*J. Iron and Steel Inst.*, 1938, Special Report No. 22, Symposium on Steel Making, pp. 248, 539.)³

the many variables introduced by the process. The determination of this relationship for any furnace investigated is a first step in the study of its fuel efficiency. Figs. 1 and 2 are illustrations taken from steel making practice in open hearth furnaces.

The determination of the heat balance can be made according to the methods outlined in British Standards 979 : 1941. From the heat balance an indication can be obtained of the directions in which improvements can be made to save fuel. In hearth furnaces, for example, it can be learnt that apart from heat in the waste gases the greatest loss of heat occurs in the furnace structure, and that the solution of the problem lies in the refractories used. Heat losses have also been reduced by the application of the waste heat boiler to the hot gases leaving the furnace system. A typical series of heat balances is shown in Table 1. A line diagram of a typical fixed furnace is shown in Fig. 3.

Modern methods of furnace control involve the use of instruments. Instruments virtually maintain a constant indication of the critical rates of input and of draught and temperature conditions. This service amounts to a watch over features of the heat balance that are of most importance in achieving efficient operation. The instruments used, in order of importance, are:

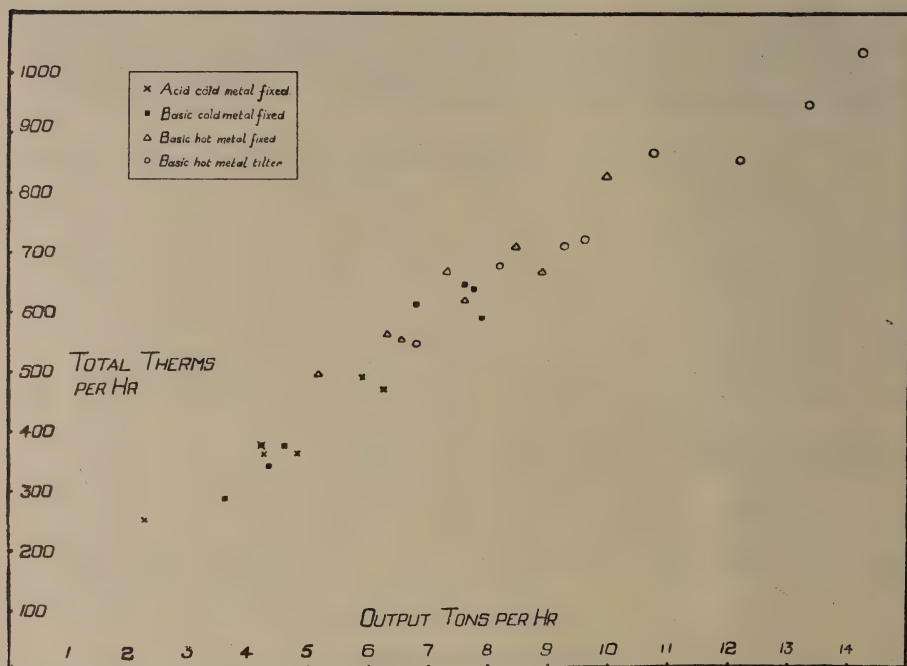


FIG. 2. Relation between the total heat input to the laboratory of open hearth furnaces and rate of output.

(*J. Iron and Steel Inst.*, 1938, Special Report No. 22, Symposium on Steel Making, "British Open Hearth Data and their Correlation," O. H. Committee, Iron and Steel Industrial Research Council.)³

(i) Fuel and air measuring appliances and pressure and draught gauges. These serve to assist the maintenance of the correct rates of firing and conditions of balanced draught necessary to avoid wasteful leakage of gas and air.

(ii) Temperature control of the molten bath or of the furnace lining by means of thermocouples, radiation and optical pyrometers which are of use from the aspect of process as well as fuel efficiency.

(iii) Indicating and recording pyrometers for observing the temperatures in the regenerative or recuperative system. Such instruments indicate unsatisfactory temperature conditions not only in degree but also in distribution, and ensure the correct timing of the reversals in regenerative practice.

Automatic controls for correct admixture of fuel and air, for correct draughting and for reversal in regenerators, are coming gradually into use as the technical difficulties of applying delicate instruments to heavy industrial processes are being overcome.

Recent developments in mechanization and instrumentation have resulted in improvements in the all-round efficiency of melting furnaces. The use of improved pyrometric control, based on radiation measurements of the temperature on the internal refractory surfaces, to control the fuel input, has led to conditions where the surface may be operated continuously up to the safe limit of the roof temperature, thereby securing enhanced rates of heat transfer. Control based on the temperature of the regenerator chequerwork can also be made automatic.

Combustion control has been introduced by the air/fuel ratio controllers based on flow meter readings actuating various types of servo mechanisms. This can be further developed to make fully automatic control of combustion

possible. Related to combustion control is the important aspect of measurement and regulation of furnace pressure. With the development of sensitive measuring techniques it is now possible to operate main exhaust damper settings from pressure recordings. This can be done by electrical, pneumatic,

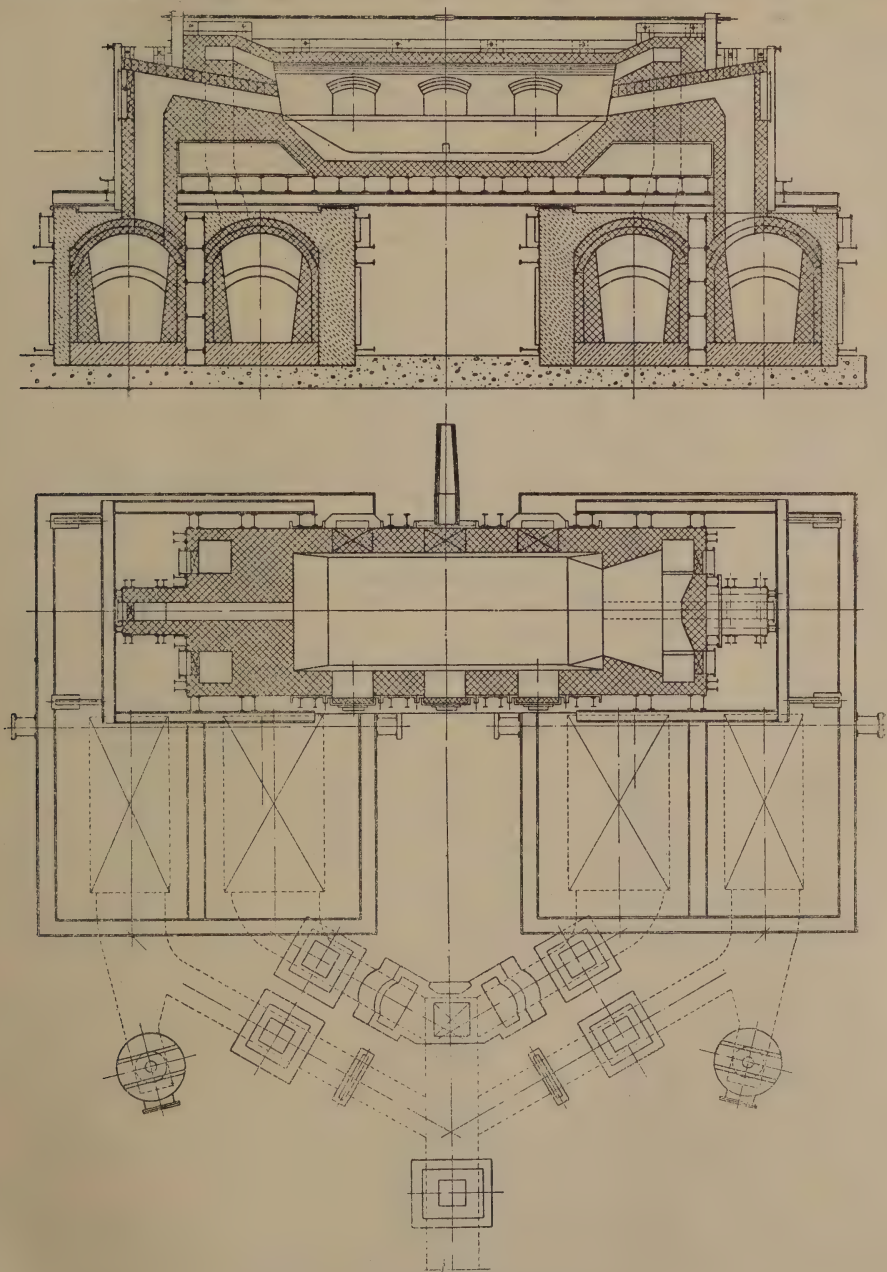


FIG. 3. Open hearth furnace.

TABLE 1. HEAT BALANCES OF OPEN HEARTH FURNACES

HEAT LIBERATED		HEAT ABSORBED			
	1	2	3	4	
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
HEAT BALANCES OF FURNACE PLANT					
<i>Heat from Fuel :</i>					
Coal to producers ..	90.1	91.9	94.3	94.5	13.4
Live steam to producers ..					
Exhaust steam to producers ..			5.7	5.5	
<i>Heat from Metallurgical Reactions :</i>					
(i) Oxidation of metalloids ..	8.1	7.7			14.9
(ii) Slag formation ..	1.8	0.4			
<i>Heat Losses :</i>					
Furnace structure :					
(i) Bath and port ends ..				34.5	43.5
(ii) Gas and air chambers ..				15.3	
(iii) Downtake flues, etc. ..				—	
(iv) Water cooling ..				3.4	33.6
Stack Losses :				7.2	
(i) Chimney gases ..				15.35	
(ii) Boiler losses ..				50.1	16.1
(iii) Heat recovery—live steam ..					3.3
Steam to engine ..					18.7
	100.0	100.0	100.0	100.0	100.0

TABLE 1 (continued). HEAT BALANCES OF MOLTEN BATH

	5 <i>Basic practice Per cent.</i>	6 <i>Acid practice I Per cent.</i>	7 <i>Acid practice II Per cent.</i>		5 <i>Basic practice Per cent.</i>	6 <i>Acid practice I Per cent.</i>	7 <i>Acid practice II Per cent.</i>
Thermal efficiency based on							
heat input at furnace valve	16.1	10.1	8.76	Steel	80.2	91.2	81.5
Oxidation of metalloids ..	32.25	57.3	44.1	Slag ..	15.4	4.0	8.9
Slag formation ..	4.50	1.2	1.9	Decomposition of limestone		1.0	0.9
Balance from fuel ..	63.25	41.5	54.0	Reduction of iron oxides..	4.4	3.8	8.7
	100.0	100.0	100.0		100.0	100.0	100.0

The data given in this table are derived from the following sources, the reference numbers corresponding to those at the heads of the columns: (1) Clements, *J. Iron and Steel Inst.* (1922). (2) Kinney and McDermott, South Works, Illinois Steel Co. (3) Combination of gas producers, furnace and waste heat plant, Barnes and Sarjant, *J. Iron and Steel Inst.*, Special Report No. 22, p. 271. (4) *loc. cit.* p. 272. (5) p. 273. (6), (7), p. 274.

or hydraulic amplification, which enables the input and output of the furnace gases to be operated by a master control.

FUEL SAVING IN OPEN HEARTH FURNACES

Notes here given were designed for practical guidance in the operation of hearth furnaces, in particular for steel making, but they have a general bearing on all types of regenerative hearth furnaces.

The problem of saving fuel in open hearth furnace practice is inseparable from problems of steel output and refractory consumption. Apart, however, from alterations in furnace design and construction, there are points to be noted in practice which tend to reduce the fuel consumption without adversely affecting output or wear of brickwork and may benefit either or both. A number of these are set out below.

- (1) Gas pressure should be kept at the pressure consistent with the required rate of output for optimum working.
- (2) Culverts, valves and furnace brickwork from producers to gas ports should be examined regularly, and repaired when necessary. There should be no leakage at these places.
- (3) Combustion in the furnace needs special consideration. Correct mixture of gas and air is essential to give the maximum heat to the bath. If the air and gas are not measured, or the ratio of air to gas is not indicated on an instrument, the flame should be closely watched. It should be highly luminous and not unduly long; the tip should on no account reach the outgoing block; it should give the maximum practicable coverage of the hearth. Too long a flame results in damage to the outgoing ports and tends to overheat slag pockets and chequers.
- (4) A slight pressure but not an over-pressure should be kept up in the furnace. A slight pressure prevents excessive cold air from being drawn in, and saves the amount of fuel necessary to heat the air up to furnace temperature. An over-pressure forces too much flame through openings in the furnace structure, wasting heat outside the furnace and damaging structural steel and brickwork. Normally, a slight flicker of flame visible at the doors is used as an indication of correct pressure. Dampers are the means of controlling the pressure. They should, therefore, be arranged to work easily and should be adjusted according to the amount of gas being burnt. The more gas used the greater the quantity of waste gases formed, and consequently the wider the damper must be opened to give the extra draught required to clear the furnace.
- (5) Gas ports and slopes should be fettled frequently in order to maintain correct alignment and flame direction. The importance of this is often not fully realised but can easily be proved by trial.
- (6) Reversals should normally be made at regular intervals, although this procedure should be modified if the chequer temperatures have become unbalanced. The object to be aimed at is even heating across the bath and this is much easier to attain if the corresponding chequers at each end of the furnace are approximately equal in temperature. Temperature recorders and controllers installed in the chequer system greatly assist the melter in balancing operations.
- (7) As much information as possible relating to the draught in the furnace system should be obtained. If the pressures and draughts are known at various points when the furnace is going well, the knowledge can often be used to diagnose complaints when the furnace is not going well. For this purpose holes should be cut through the brickwork and fitted with

easily removable plugs. Readings with a draught gauge may then be taken regularly. Suitable points for the test holes are:

- (a) in gas and air uptakes—say a foot or so above stage level,
- (b) in gas and air slag pockets,
- (c) above gas and air chequers,
- (d) in gas and air culverts as near base of chequers as practicable,
- (e) in the stack flue near the damper and on the furnace side of the damper,
- (f) before and after the main gas valve, for obtaining drop in pressure across the valve.

As examples of information obtainable from such readings, if the difference between the pressures before and after the main gas valve is higher than usual, the flow of gas through the valve is being impeded and the valve housing needs inspection and clearing. If the difference between the waste gas draughts taken above and below a set of chequers is greater than usual, the chequers are becoming choked.

- (8) CO₂ recorders are of doubtful value when applied to the waste gases of an open hearth furnace. But analyses should be made to check correctness of combustion and incidence of air inleakage. If, about an hour after the furnace has been fully charged, Orsat samples are taken through a silica tube inserted into the gas downtake, reliable figures may be obtained. Normal CO₂ content at this point is 15–16 per cent. when operating on producer gas. Care must be taken that no air is drawn into the uptake around the silica tube.
- (9) Instruments to record draughts and pressures continuously are very useful especially when simultaneous readings taken at two or more points are necessary for accurate comparison. But for a permanent installation it is preferable to have a limited number of recorders, including one showing the gas pressure and another the effective stack draught, rather than a multitude which may confuse rather than inform. A modern furnace would have a system of automatic control which might well render all these provisions unnecessary. In effect, in one and the same composite system it would control the rate of fuel input into the optimum value, and regulate the air/fuel ratio, temperature and draught to give the desired conditions automatically. It is when instruments fail that field survey methods have to be called into service.

It cannot be stressed too strongly that improvement in fuel consumption of open hearth furnaces depends as much on past as on present knowledge. Data concerning a particular furnace collected when it is going badly may be of little or no value unless they can be compared with similar data obtained when it was comparatively new and efficient. Someone should be responsible for the collection and collation of such information. Fuel consumption, steel output, gas pressures and draughting conditions should be observed and set down weekly. This can all be done quite quickly once a routine is established, and the results, arranged as tables, curves or in any other way suitable for easy comparison, will soon be regarded as essential to the attainment of minimum fuel consumption.

CRUCIBLE FURNACES

Crucible furnaces are fired by coke, gas or liquid fuel, the main consideration in high temperature work being that the fuel must be able to give a high intensity of combustion since the quickest melting is usually the most economical in both fuel and metal.

COKE FIRING

The size and quality of the coke is a factor of major importance. The manner of combustion of coke is related to its physical properties, the harder cokes in a limited supply of air burning with a higher ratio of carbon dioxide to carbon monoxide in the products of combustion, and so giving a higher intensity of combustion. Hard cokes of low reactivity are specially suitable for high temperature melting operations, e.g. for crucibles, reverberatory furnaces and cupolas.

For discussion of reactivity and combustibility of coke the reader is referred to the literature. It is a subject to which considerable investigation has been devoted. One of the best means of revealing a hot melting coke is the determination of the shatter test, a high resistance being required.

When coke is burnt on grate bars its ash content, its refractoriness, suitability of grading or size analysis, the draught available and the critical rate of combustion required to give quick melting must all be considered in relation to the work in hand. In the older type of natural draught crucible furnace or pothole, fired by coke, due to limitations of design the old beehive coke gave the most satisfactory and economical melting at the highest temperatures, but with adequate draught and a suitable size of coke, by-product oven coke is equally effective, provided a clean coke of low reactivity and good shatter resistance is used. The sulphur content of the fuel must be limited.

The quantity of coke charged at each feed and the draught must be adjusted to follow the course of the heat, so that fresh charges are not required just as the heat is nearly ready.

A suitable specification for a coke of good melting quality is as follows:

Moisture	As low as possible.
Ash	8 per cent.
Sulphur	Under 1 per cent. (Purity and good shatter index permit a higher sulphur content to be carried.)
Shatter index	1½ inch index as high as practicable and preferably over 90 per cent.
Size	Less than 6 per cent. through 2 inches, the remainder being as close graded as practicable for the particular size desired.

GAS AND OIL FIRING

With oil-fired or gas-fired crucible furnaces the use of the correct rate of fuel consumption and fuel-air ratio is of prime importance. Fuel is wasted if either too much or too little fuel or air is used. The optimum conditions are indicated from the shape and colour of the exhaust flame, and gauges indicating flow, pressure and draught are called for to assist control. A burner out of line will readily cause waste of fuel, as well as spoil metal.

The size of crucible, and shape and dimensions of the combustion chamber and off-take flues are primarily matters of initial design, but in many operations are amenable to alteration at rebuilds. Preheater tops, made from an old crucible are sometimes employed with the object of getting the whole of the charge into the furnace at the start of the heat. Worn linings should be constantly kept in repair, carbon deposits prevented from forming in combustion chambers and all leakages avoided.

SHAFT FURNACES

The most important shaft furnace is the blast furnace for the smelting of metals from their ores, but since this type of furnace is of specialized type, and its operation is bound up closely with a complicated metallurgical operation, it is not considered in this book.

Another important type of shaft furnace for melting purposes is the cupola furnace.

THE CUPOLA FURNACE AND FUEL ECONOMY

The cupola has a relatively high thermal efficiency when compared with

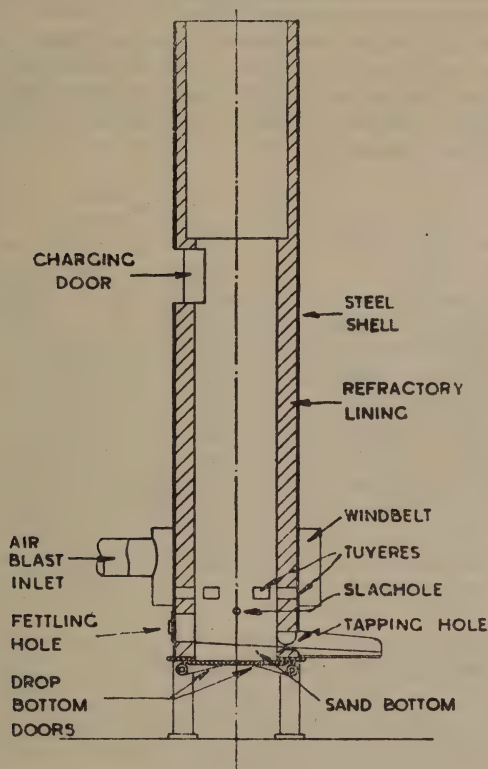


FIG. 4. Drop bottom cupola.

other coke-fired melting furnaces and, because it will give reasonably satisfactory results even when inefficiently operated, it is sometimes found that little attention has been paid to design and operation. It is intended here to show how design and operation can affect the thermal efficiency of cupolas and consequently their fuel consumption.

DESIGN

The cupola (Fig. 4) consists of a mild steel shell erected in a vertical position and lined with refractory. The shell is mounted either on a brick foundation or on steel columns. The steel column arrangement is used on most modern cupolas and the bottom of the shell is provided with drop-bottom doors, through which the debris, consisting of coke, slag, etc., can be discharged at the end of a melt.

In drop-bottom cupolas, the working bottom is made up with moulding sand which covers the drop doors. This bottom slopes towards the metal tap-hole at the front of the cupola, the tap-hole being at the lowest point. The sand bottom is put in through a hole in the shell at the back of the cupola opposite the metal

tap-hole. This is known as the *fettling hole* or cleaning-out door, and in solid brick-bottom cupolas is also used for raking out the debris at the end of the melt.

Tuyères for supplying the air blast are provided between 2 and 4 feet above the working bottom. The air is delivered to the tuyères from a wind belt, which surrounds the shell. A high pressure fan, or a positive blower, supplies the air to the wind belt through a blast pipe. A valve is provided in the blast pipe so that the air supply may be controlled.

A slag hole is located at a level about 9 inches below the centres of the tuyères. A charging hole is provided through which metal, coke and flux are fed into the furnace; this is situated 10 to 20 feet above the tuyères, according to the size of the furnace. The shell is usually continued for 15–20 feet above the charging hole to form a chimney.

OPERATION

In preparing the cupola for a heat, a fire is lighted on the working bottom and a bed of coke built up to a level just above the tuyères. This coke bed must be thoroughly hot before it is finished off to its final height. The fire may be drawn up by natural draught, or a forced draught may be used, supplied by a small auxiliary blower or by means of kindling tuyères from the wind belt. As soon as the fire is well alight, the fettling hole is closed up with sand and a cover plate fixed over it. The coke at the tuyères must be well heated before charging begins. It is advantageous to finish off the bed with about 12 inches of cold coke to bring it to its correct level. This level should be checked by means of a measuring stick inserted at the charging hole. When the bed is completed, the cupola should be charged full to the sill of the charging hole before the blast is put on. Alternate charges of metal, coke and flux are used until the cupola is full. When the metal in the cupola starts melting, the rate of charging should be equal to the rate of melting, so that the furnace is kept full throughout the heat.

The metal should begin melting in five or six minutes after the blast is put on. The molten metal may be collected in the well of the furnace below the tuyères and tapped off as required, or allowed to run from the furnace as it melts and collected in a ladle or receiver. When slag accumulates in the well, the slag hole is opened and the slag run off, preferably into a bogie for easy removal.

At the end of the melt, charging is stopped and the blast is kept on until all the metal has melted. A careful watch should be kept at the tuyères and the blast should be shut off immediately it is seen that no more metal is melting. If this is not done, coke which could otherwise be recovered is wasted. By far the greater part of the damage to the lining takes place during this emptying or "blowing down" period, and unless the blast is shut off as soon as all the metal is melted, the wear on the lining will be increased.

As soon as the blast is shut off, the debris should be discharged from the cupola, either by dropping the bottom doors, or, in solid-bottom cupolas, by removing the fettling hole cover and raking out. The debris should be immediately quenched with water, using an ample supply. Care should be taken to see that it is completely black before the water is turned off. It is frequently found that the draught through the cupola will draw up any remaining embers and re-kindle the coke, which will then burn away during the night. When the debris is cold, usually the next morning, it should be hand-picked and the coke remaining returned for use in the cupola. This coke has not suffered in any way by being used in the furnace, tests having shown that it is not contaminated by any deleterious elements and is quite suitable to be used along with new coke to make up the charges.

TUYÈRES

The total area of the tuyères should be one-fourth to one-seventh of the cross-sectional area of the cupola inside the lining at tuyère level. The shape of the tuyères, whether round, rectangular, flared or parallel, has little influence on the efficiency of the furnace, so long as an adequate area is provided inside the lining. Some cupolas are provided with tuyères in one row; others have two or more rows. In the balanced blast and Poumay types, using multiple rows of tuyères, those in the upper rows are provided to admit air for the more complete combustion of the coke to carbon dioxide. In other types, the use of a double row of tuyères means only that an additional quantity of coke is required for the bed each time the cupola is used. Unless a specially high pick-up of carbon is required, necessitating the use of a deep bed, this wastes fuel.

For the melting of high steel charges for the production, for example, of steel by the converter process, a high carbon content is not required, and tuyères arranged in a single row will give the best results.

INTERNAL DIAMETER AND HEIGHT

The internal diameter of the furnace at the tuyères and in the melting zone controls the output obtainable from the cupola. This assumes, of course, that the air supply is adequate for the operating diameter. In normally operated cupolas, an output of 0.7–0.8 ton per hour is obtained per square foot of cross-sectional area in the melting zone. When melting high steel charges, however, the rate of melting is reduced, and it is also desirable to operate the furnace more slowly than is possible on pig and scrap-iron charges. The output when melting charges containing 80–100 per cent. steel is seldom more than 0.5 ton per square foot cross-sectional area per hour.

The shape of the lining is important and is governed by several factors. In cupolas which are tall between tuyères and charging hole, a parallel lining from base plate to charging hole may be used, and this also holds for cupolas where a low output is required for the internal diameter. In short furnaces, and where a high rate of melting is required, a boshed lining is desirable. The holding capacity of the furnace for solid metal, coke and flux to a large extent controls the temperature at which the exhaust gases are discharged. The smaller the amount of stock held in the cupola, the hotter the exhaust gases and the greater the loss of heat from the fuel used. Except in very small cupolas, i.e. less than 24 inches internal diameter, where there is a danger that the stock will bridge and hang up in the furnace, the pre-heating zone above the coke bed should hold metal, coke and flux sufficient for one hour's melting.

Many cupolas are short between tuyères and charging hole and owing to the short pre-heating space, the gases escape at a very high temperature and the thermal efficiency is relatively low. Conditions in these can be considerably improved by increasing the internal diameter from a level near the top of the bed coke and maintaining this increased diameter up to the charging hole. The thickness of the brickwork in the expanded portion must not be reduced below, say, 6 inches on cupolas of 5 tons capacity, or 9 inches on large cupolas. The area in the expanded portion may be 30–40 per cent. greater than in the tuyère zone. The flare from the smaller to the larger diameter should be gradual and is usually made about 2 feet 6 inches deep. Because of the loss of heat when the stock column is short, it is essential to keep the cupola fully charged throughout a melt.

A boshed lining makes it a little more difficult to separate different mixtures when irons of a number of different compositions are melted in one heat. It is also not desirable, when a cupola is completely emptied and re-charged several times a day. Because of the additional bed coke required and the severe wear

caused at the lining, this latter method of operation should be avoided whenever possible.

An alternative to increasing the internal diameter in the pre-heating zone is to increase the height of the charging hole, but this usually necessitates major alterations to the charging platform and hoisting equipment. However, in some cupolas, operating for long periods, which are very short to the charging hole, it may be worth while to reconstruct the furnace to enable one hour's supply of metal to be stored in the pre-heating zone.

REPAIRS TO LINING

During every melt in a cupola, part of the lining, especially that in the zone of maximum temperature immediately above the tuyères, is slagged and eroded away. This material must be replaced after each melt by patching with ganister and/or firebricks or ramming round a former. Whichever method of repair is adopted, the furnace should be brought back to the same internal dimensions each day. Slipshod repair work causes increased fuel consumption as well as short life of the lining and troubles in operation. If the repair work is poor and insufficiently dried out before the cupola is put to work, the new material will rapidly come away and heat must be consumed in converting it into slag.

A more important point is that if the internal dimensions are allowed gradually to become larger, more coke is used on the bed. The efficiency of the furnace may also suffer, thus necessitating the use of more coke to produce metal of a suitable temperature. Whether the furnace is being patched to its correct dimensions can be found by occasionally checking the weight of coke required to bring the bed to its correct height.

HEIGHT OF COKE BED

The height to which the bed coke is built up above the tuyères is an important factor in controlling the temperature of the metal from the first tap and also from subsequent taps. Other things being equal, a low bed will yield cooler metal than a high one. A bed height of 2 feet above the tuyères, that is, above the top row of tuyères if two rows are used, is somewhere near the minimum height which may be employed. Where extremely hot metal is required, or where a high pick-up of carbon is desirable, a bed height of 4 feet may be necessary. In exceptional cases, as for example in producing metal for white-heart malleable castings, an even higher bed may be required and it is, of course, false economy to jeopardize the temperature and quality of the metal by starting with a bed which is too low.

METAL AND COKE CHARGES

The weight of the metal charges has some influence on the efficiency of the furnace. A large number of light charges will, under certain conditions, give a lower thermal efficiency than a smaller number of heavy charges. No hard and fast rule can, however, be laid down regarding the size of charges for various sizes of cupolas as this depends largely on the type and quality of the metal being melted. The heaviest charge a cupola will melt successfully is about one-sixth of its hourly output, but it is often advisable to use charges one-tenth or less of the hourly output.

All metal charges should be weighed. The coke charges should also be weighed, but it is sometimes difficult to provide the necessary labour and other facilities. In such cases, the coke should be measured in a skip. If the skip is of a suitable size, that is, just holding the correct weight of coke for a charge, this method of measuring will be found almost as accurate as weighing. Careful control of the weight of metal and coke is well worth while as it not only invariably results in a saving of fuel, but is also often found to yield an increased

output and metal of a more uniform temperature throughout the heat. On the other hand, measurement of coke by the number of shovelfuls or fork loads charged is unsatisfactory and usually leads either to a waste of fuel or to fluctuating metal temperature. The flux, usually limestone, should be approximately 25 per cent. by weight of the coke charge and may be weighed or measured in the same way as the coke.

COKE RATIOS

If all metal charges are weighed and the coke either weighed or measured accurately by volume, it is possible to assess the ratio between metal melted and coke charged. This ratio depends on a great number of factors, including the design of the furnace, amount of preheating space available and so forth; the type of metal to be melted, size of individual pieces, amount of steel scrap included in the charge, etc.; the quality of the metal, e.g. whether high or low phosphorus, or whether a high carbon pick-up is required. Generally speaking, the smaller the size of the pieces of metal charged, the lower the coke consumption in melting them. Large pieces should therefore be broken as far as this is possible. The higher the percentage of steel melted, the more coke is required to melt and carburize it.

Very small pieces of steel, such as punchings, oxidise very easily in the cupola and necessitate the use of additional coke if they are to be melted successfully. Owing to the difficulty of accomplishing this, even under the best conditions, their use should be avoided. Very heavy steel scrap requires a high coke consumption to ensure that pieces are completely melted before they descend to the oxidising zone near the tuyères. If a high carbon pick-up is required, the coke consumption will generally be high, as carbon must then be supplied to be taken up by the metal. Cupolas operated intermittently with frequent shut-downs will require more coke than those run continuously.

Owing to the large number of factors involved, it is not possible to give definite recommendations for the ratio of metal melted to coke charged which can be achieved on different classes of work. The following table is intended only as a guide and shows good average practice in the industry.

<i>Class of work</i>	<i>Metal-to-coke ratio</i>
High-phosphoric iron for fairly heavy castings ..	12:1 to 15:1
High-phosphoric iron for light castings ..	11:1 to 14:1
Medium-phosphorus iron for engineering castings	10:1 to 12:1
Low-phosphorus iron for high duty and automobile castings	8:1 to 10:1
Charges containing 50–75 per cent. steel scrap ..	7:1 to 9:1
Charges containing more than 75 per cent. steel Scrap	6:1 to 8:1

In examining the overall coke consumption in a cupola, the coke used on the bed must be taken into consideration. The coke recovered from the debris at the end of the melt should be deducted from the total weight of bed coke used. As the same amount of bed coke is required whether the furnace melts 5 or 50 charges, it will be seen that the overall coke consumption depends to some extent on the length of the heat, and coke consumption per ton of metal melted will be less on long than on short heats. In very small foundries, therefore, where it can be arranged, it is better from the fuel economy point of view to have a long heat every other day than a very short heat each day.

Modern trends in cupola practice have brought into question the correct sizing of coke for cupolas, the optimum rates of melting and the most desirable properties to be looked for in the coke. Hot blast, oxygenated blast and the

use of basic refractory linings have all been successfully applied in practice. This pre-heated air obtained from a recuperator fed by the throat gases enables a marked increase in rate of melting to be attained. The use of blast enriched with oxygen provides a ready control of metal temperature. In the basic lined cupola the materials used have been magnesite, dolomite and stabilized dolomite. External water cooling applied in the region of the melting zone has resulted in economy of refractory materials. These specialized applications have introduced considerations relating to metallurgical process and accordingly the reader is referred to more specialized works for the full treatment of the subject.

In conclusion, nothing is so conducive to fuel economy and overall economy in foundries as the use of metallurgical coke of high and uniform quality. If the quality fails, the consumption is increased, with its consequence of increased cost of operation and transport; the metal quality and temperature suffer as a result of the increased sulphur and ash content of inferior fuels. Foundry coke is not only a fuel, but a technical material, the quality of which affects the quality of the metal melted.

SINTERING FURNACES

The cement kiln may be regarded as the most typical example of the application of heat for sintering. It concerns also an important industry. The following statement outlines the methods of operation and maintaining efficiency in rotary cement kilns.

ROTARY CEMENT KILNS

Rotary cement kilns as used in the cement industry, consist of cylindrical furnaces supported on rollers (Fig. 6). They vary in length from about 150 feet to something like 500 feet, and in diameter from 7 feet to 12 feet.

Nearly all cement works in this country are working on what is called the "wet process," in which the raw materials are fed into one end of the kiln as a wet slurry and, owing to the rotation and inclination of the kiln, gravitate slowly towards the other end, where they emerge as clinker.

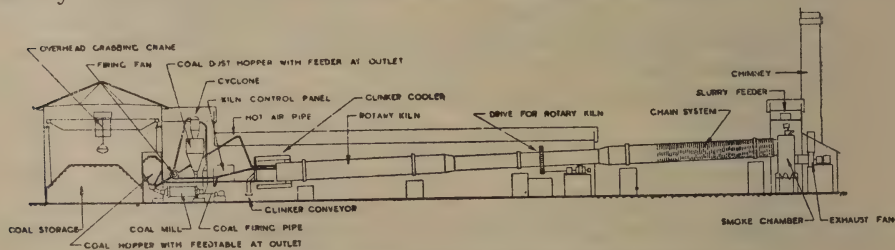


FIG. 5. Rotary cement kiln fired by pulverized coal.

The fuel used in cement kilns in Britain is pulverized coal. Fuel oil or natural gas are also used sometimes in some countries.

The raw materials fed into the upper end of the kiln may contain between 36 and 43 per cent. of moisture. When entering the kiln, the slurry meets the hot combustion gases, the water is evaporated and later, when the material reaches a temperature of 1,650° F. (900° C.), the carbon dioxide is driven off; finally, the material is heated to about 2,650° F. (1,455° C.) in the hottest part of the kiln where the chemical reactions take place that cause the formation of the product—cement clinker.

The clinker is generally cooled through a clinker cooler which either forms part of the kiln or is a separate unit. It is cooled by means of an air current and,

therefore, a substantial part of the latent heat contained in the clinker is recuperated and used for preheating the secondary air required for burning the coal in the rotary kiln.

In order to produce the necessary chemical reaction and thereby give the required strength of the cement, it is essential to reach the above-mentioned temperature of about 2,650° F. (1,455° C.). This temperature is close to the fusion point of the refractories, and were it not that it is possible to build up a coating of cement clinker on the refractories it would be difficult to get any lining material to withstand the heat and the abrasion.

Provided complete combustion is obtained with a minimum of excess air, and the moisture content of the slurry is kept as low as possible, fuel saving can only be looked for in lowering the temperature of the exit gases and of the cooled clinker.

To lower the temperature of the exit gases, cement kilns are generally provided with a drying zone, which may have chains or other devices for increasing the area opposed to the gases; external driers are also sometimes used. There is little the operator can do to effect a saving of fuel in this part of the kiln other than to see that chains and other drying elements are kept in as efficient a state as possible. This also applies to the recovery of heat in the cooling of the clinker.

The coal consumption in rotary cement kilns operating on the wet process may vary from about 24 per cent. to about 32 per cent. when based on a coal having a calorific value of 12,500 B.t.u. per lb. The variation may be due to different factors, such as varying moisture content of the slurry, nature of the raw materials and the efficiency of the kilns. To improve the kiln efficiency would necessitate a considerable amount of reconstruction which it might be difficult to undertake.

Most cement works use a gas coal having a volatile content of about 25–30 per cent. The coal should have as low a moisture content as possible, depending on the facilities for drying and grinding it, and the fineness should be about 15–20 per cent. residue on a 170-mesh sieve. Ash content should preferably be as low as possible, but it should always be of such a nature that it will assist in forming a protective coating on the refractory lining.

If coal having too high an ash content, or ash of an unsuitable nature, is used, it frequently leads to the formation of clinker rings, which not only tend to reduce the output of the rotary kilns, but also lead to inefficient combustion and incomplete burning of the clinker.

To ensure complete combustion, cement manufacturers generally reckon that it is advisable to have about 1 per cent. of oxygen in the exit gases. Frequent analysis of the exit gases should be made, and an oxygen recorder will be found a valuable instrument for checking the combustion. It is very important to ascertain that samples of the exit gases are truly representative; experience has shown that the most representative sample is extracted in the upper left-hand quarter when looking at the kiln from the back and assuming it rotates in an anti-clockwise direction. Where two or more coals of widely varying qualities are used, it is essential for them to be well mixed so as to minimise variations in volatile contents, ash, and so forth; otherwise unstable conditions are set up in the kiln, causing incomplete combustion. Provided really good mixing facilities are available, it is possible for cement works to use a proportion of anthracite having a volatile content as low as 6–8 per cent.

KILNS

Kilns are the structures used for the heating or firing of a number of important products, particularly those made by the pottery and heavy clay industries from clay or a mineral base. Differences in the type of kiln, together

with great differences in the thermal requirements of the raw materials used to obtain the properties desired in the fired ware involve perhaps a greater number of problems specific to the process used than are associated with any other type of heating appliance. This is accentuated by the fact that the production of high yields of first quality ware is usually of major importance. Specifications^{4,5} for the testing of kilns used in the heavy clay and pottery industries have been issued by the British Standards Institution. Reference to these standards will indicate those features which have to be watched in order to maintain or improve thermal efficiency. It is not proposed to deal here with the efficiency of such plant in a detailed way, but mainly to indicate certain outstanding factors affecting fuel economy.*

In the firing of all clay wares it is necessary to maintain a specific time-temperature schedule determined by the thermal requirements of the material, to obtain uniform heating and control of the process involved and control the kiln atmosphere to give oxidizing or reducing conditions as required to produce the desired changes in the ware.

Three stages of heating are almost invariably involved:

- (1) The water smoking period in which appreciable volumes of hot air must be passed through the setting in order to remove moisture until the ware is completely dry.
- (2) The oxidation or preheating period in which chemically combined water is removed and oxidation of any carbonaceous matter in the green product is safely completed.
- (3) The finishing period during which the required final temperature is attained and soaking time allowed at the finishing temperature to obtain uniformity of heat treatment and develop the degree of vitrification or maturing properties required. Distinctive methods of pyrometry are used to determine when correct finishing conditions have been reached, e.g. standard pyrometric cones or other heat recorders are used to measure the "heat-work" performed.

In each of these stages, the combustion conditions used are governed by special requirements for different classes of goods and the firing technique required usually differs markedly from that used in other types of heating plant. Firing methods also depend on whether intermittent or continuous kilns are used and on the applicability or availability of automatic firing mechanism.⁸ Intermittent kilns are mainly used to fire special products not amenable to continuous practice or to secure flexible treatment on a works manufacturing a variety of products where flexibility is of more importance than high thermal efficiency or large output of any one product. Unavoidable heat loss from the firing of these kilns is considerable. Continuous kilns are specially applicable to the firing of standard products where large throughput is desired. Recuperation of heat from cooling goods and from the kiln gases makes firing in this kind of kiln an operation of high potential thermal efficiency. Kilns of both classes are used in each branch of the industry, but there are often differences in the actual types favoured.

In Britain the use of mechanical stokers is largely confined to continuous kiln practice.

TYPES OF KILN AND OVEN

(a) *Intermittent Kilns.* Two main types of intermittent kiln are used in the heavy clay industry: the rectangular down-draught and the round down-draught. Both muffle and open-flame conditions are used with each type. In

*The reader is referred to the publications of the British Pottery and British Refractories Research Associations—now amalgamated as the British Ceramic Research Association.⁶

muffle firing the gases from the fires are not allowed to make contact with the goods being fired; heat transfer being obtained almost entirely by radiation from the muffle walls. With open-flame firing, which is used to a much larger extent, all gases and flames from the fires pass through setting spaces among the ware before the combustion products are finally exhausted through the flue system. Apart from the shape and type differences generally recognised, intermittent kilns vary widely in size and in the arrangement or disposition of the sole flue system.

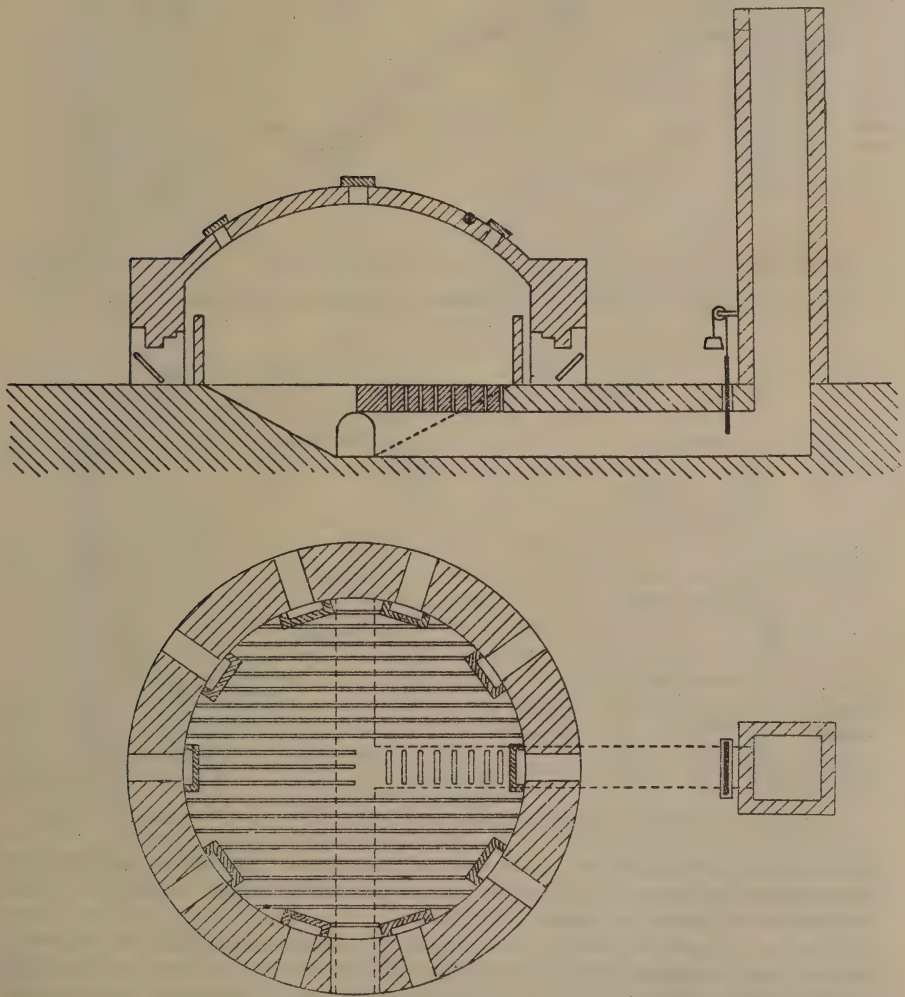


FIG. 6. Down-draught kiln for firing heavy clay ware.

Each kiln is usually connected to a separate stack, generally external to the kiln, though a central internal stack is used sometimes. The draught in the kiln is controlled by means of a damper at the base of the stack. The number and disposition of the firemouths also varies. These may be of the solid bottom type or they may be equipped with horizontal, inclined or step grates. Combination grates are also used. Modern kilns are usually fitted with fire-doors

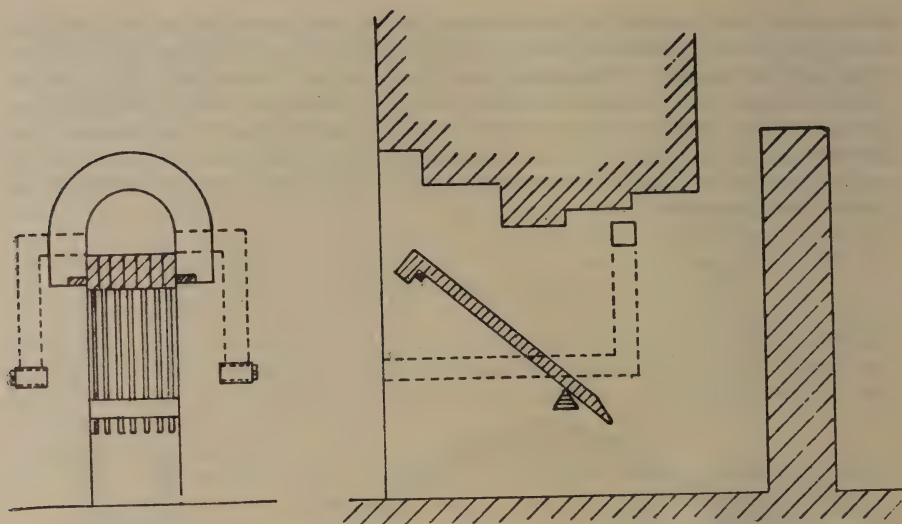


FIG. 7. Firemouth provided with inclined grate bars as used in the heavy clay industry.

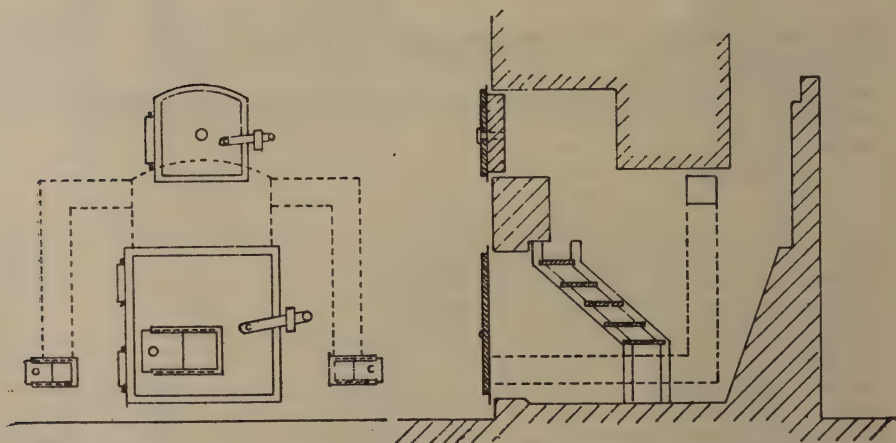


FIG. 8. Firemouth, stepped grate type, provided with top and bottom firing doors.

permitting control of primary air, and slide-controlled secondary air flues are being increasingly used. The designs of a typical round down-draught kiln and firemouths are shown in Figs. 6, 7, 8.

In pottery practice two types of kiln or oven are distinguished—the up-draught and the down-draught. Each of these types may be fired on the muffle or open-flame system. Kilns are to be found in a wide variety of forms suited to the special needs of the product fired. The disposition of the firemouths plays an important part in obtaining correct temperature distribution.

In the up-draught type of kiln, an illustration of which is given in Fig. 9, the products of combustion are evacuated through openings in the crown of the kiln. These may be surmounted by a superstructure, termed the cone, which augments the draught for operating the kiln and exhausts the gases from the various outlets. In this type of kiln a certain amount of draught is naturally provided from the stack effect of the kiln itself. Control of the firing is effected

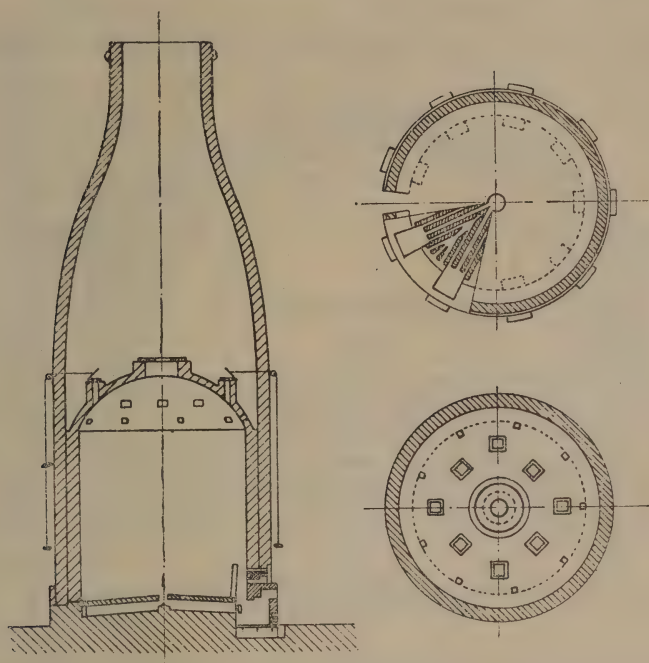


FIG. 9. Up-draught pottery kiln.

by the adjustment of check dampers placed in the outlets in the crown or other parts of the kiln. The disposition and size of kiln outlets varies appreciably.

In down-draught pottery kilns the gases from the firemouths pass over or through the ware before they are withdrawn through openings in the floor from which they travel through vertical flues between the firemouths into the cone.

In the Wilkinson type of kiln part of the gases are exhausted through openings in the crown and part through openings in the floor. This arrangement involves a combination of up-draught and down-draught conditions. Muffle kilns used for pottery firing do not differ greatly in principle from those used in the heavy clay industry, but the cone system is generally used for exhausting the waste gases, and the kilns are generally of comparatively small size.

(b) *Continuous Kilns.* The economic advantages of mass production and high thermal efficiency are obtained from the use of continuous kilns (Figs. 10, 11, 12). Because of the low fuel consumption and the refinement in control offered, advantages are sometimes obtained by firing with fuels other than coal.

Two distinct firing principles are used in continuous practice. In car tunnel kilns the pre-heating, firing and cooling zones are fixed and the goods travel through these zones on cars or bogie carriages operated by an external pusher mechanism. These tunnels may be either straight or annular, a moving hearth being used in the annular kiln instead of cars. The straight tunnel has the advantage of acting as a conveyor between factory departments and economy of labour may be combined with the efficient use of fuel. Such plant assists in maintaining a flow of material on modern mass production lines.

In the second type of continuous practice the goods are set in the kiln and remain stationary while preheating, firing and cooling zones move round the kiln. With this type, one continuous tunnel may be used as in the Belgian and

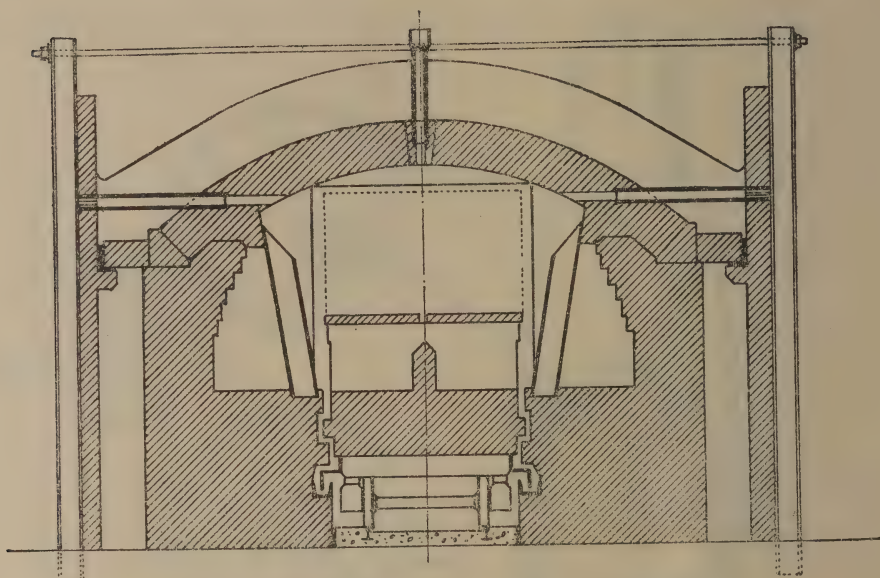


FIG. 10. Continuous car tunnel kiln: Thrift muffle
(for firing pottery ware).

Hoffman kilns or the kiln system may consist of a number of transverse arch chambers connected through suitable chamber openings. When the setting is stationary the kilns may be built to include a number of independent firing zones. Among the advantages of this system are compactness of layout and, in transverse arch chamber kilns, chambers of very large capacity may be used. Semi-continuous kilns are also used to obtain some of the advantages of continuous practice.

With all continuous kilns heat from cooling goods is used to preheat secondary air required for combustion and primary air may also be preheated in this way. Some of the heat recovered may be transferred to different parts of the kiln when more or less complicated systems of hot air circulation are used, or hot air may be transferred for extraneous use in dryers. The hot kiln gases are used to preheat the incoming or cooler ware so that the main heat losses are confined to those due to radiation, convection and conduction from the outside walls.

In the heavy clay industry, straight car tunnel kilns, ring tunnels or annular kilns, such as the Hoffman and Belgian, transverse arch chamber kilns, and semi-continuous kilns are used. Car tunnel kilns and Belgian kilns are mainly used in the refractories industry whereas Hoffman and transverse arch chamber kilns are very widely used for firing building bricks. Open-flame methods of firing are generally used for heavy clay wares. Car tunnel kilns are almost always fired from the side. Mechanical stokers are usually used for coal firing, but these kilns may also be fired by producer gas. Belgian kilns are also side fired, generally by hand, and the grate extends across the width of each chamber. The Hoffman and transverse arch chamber kilns are top fired with or without the use of fenders or grates. The coal is usually fed to charging shafts left in the setting through a series of small holes in the crown about 4 feet apart. Certain transverse arch chamber kilns are side fired and firing by producer gas is also used for better quality ware.

Continuous kilns used in the pottery industry are mainly of the straight car

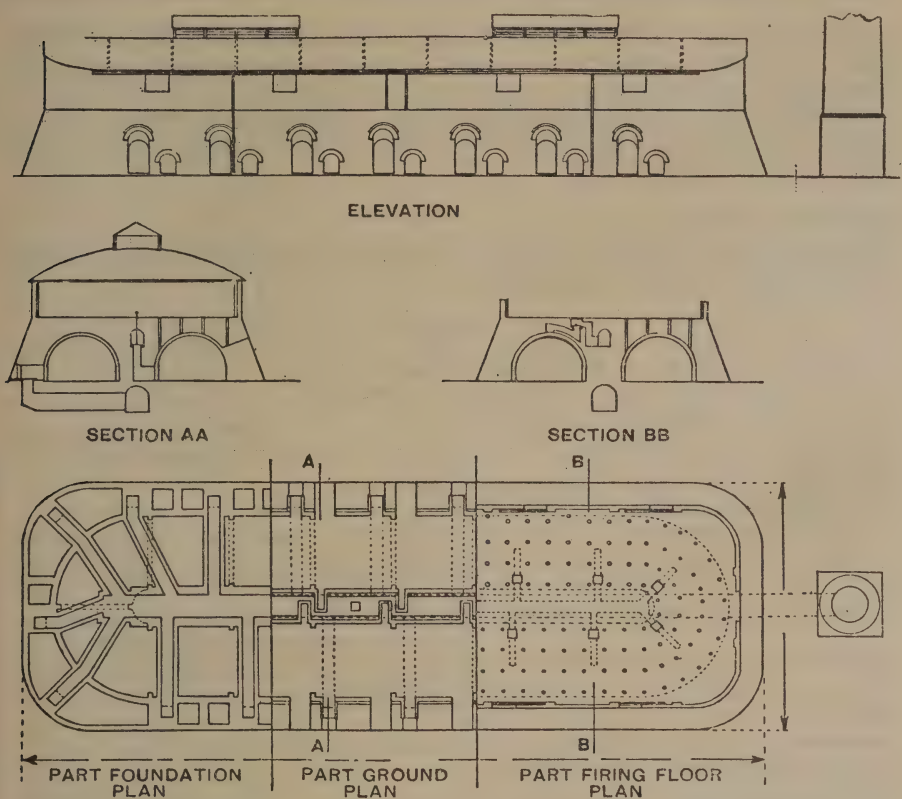


FIG. 11. Continuous ring tunnel kiln: 16-chamber top-fired Hoffmann kiln, for firing building bricks.

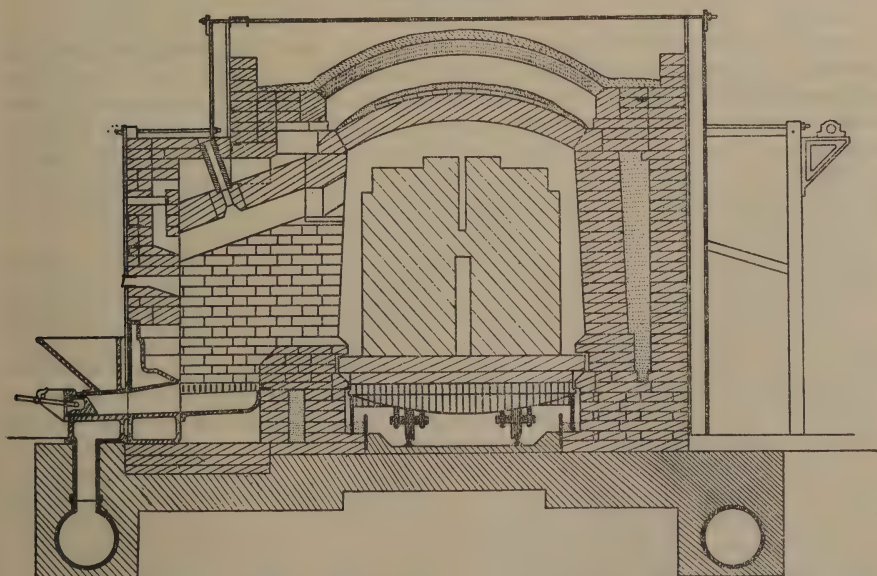


FIG. 12. Continuous car tunnel kiln: open flame, using mechanical stokers, for firing building bricks or firebricks.

tunnel type or annular type with moving hearth. Open-flame, muffle, or semi-muffle conditions of firing may be used. These kilns are generally fired with town gas or producer gas, but fuel oil and electrical heating are also used.

In addition to the above classification, kilns in the pottery industry are also classified according to the purpose for which they are used, e.g. for firing biscuit, glost or enamel ware.

FUELS FOR KILNS

The type of fuel depends on the kiln used and the material fired. General requirements are shown in Table 2.

TABLE 2
KILNS AND THEIR FUELS

<i>Kilns</i>	<i>Fuel</i>
<i>Heavy clay—</i>	
Intermittent down-draught (open-flame, muffle and semi-muffle).	Coal: fired to side mouths.
Semi-continuous kilns	Coal: fired to side mouths or top-fired; fenders or grates may be used.
Continuous car tunnel kilns	Coal: mechanically fired; producer gas; pulverised coal and fuel oil also used.
Continuous transverse arch chamber kilns	Coal: top-fired; fenders or grates may be used. Producer gas used for special products.
Continuous ring tunnel or annular kilns	Coal: Hoffmann top-fired; Belgian side-fired on to grates.
<i>Pottery—</i>	
Intermittent, up-draught, down-draught, up- and down-draught, open-flame and muffle.	Coal: fired to side mouths.
Continuous car tunnel or annular moving hearth.	Town gas, producer gas, fuel oil, electricity.

Coal is the most usual fuel for kiln firing. For most purposes, size and size grading are important. Small coal is preferred for top firing and usually for use with mechanical stokers. For stoker firing, graded coal of small size is sometimes required. For intermittent kilns larger size or size grading is often specified, although "run of mine" coal is used if the proportion of fines is not too high. Correct size grading is of special importance during the finishing period. Close grading is usually required for Belgian and fender-fired kilns. Special grates may be used to suit the type of coal available.

Long-flame coals with volatile matter content above 32 per cent. are required since radiation from long flames is conducive to uniform heating. For high thermal efficiency the ash content of the fuel should be as low as practicable. Low ash coals are specially desirable for firing to fenders and grates of the Belgian type where the ash may not be removed during the firing. Low ash content becomes more important with increased finishing temperature. Top fired kilns, such as Hoffman and transverse arch chamber kilns, can usually deal with coals of higher ash content especially if the firing temperature does not exceed 1,000° C. Swelling or strongly coking coals are not generally desirable because they restrict the flow of primary air through the fuel bed. Where small coal is used for maintaining a thick fuel bed, however, some use may be made of coking properties if the bed is poked with sufficient frequency. Fusible ash is detrimental in general practice. Coals of low sulphur content are usually required for the firing of most pottery ware.

FIRING OF KILNS

Intermittent Kilns

The principles of combustion as outlined in earlier chapters apply in this type of plant, but must be considered also in relation to the process involved.

Apart from the needs of the ware the main combustion requirements are governed by considerations of heat transfer. Until combustion can be maintained in the setting or in muffle flues, heat transfer from the fire gases is mainly by convection. Combustion of the coal should be completed in the firemouths with an excess of air. This applies to stages of the firing below about 700°C. , since flame combustion cannot be completed in the kiln.

At higher kiln temperatures heat transfer is mainly by radiation, heat transfer from long flames, as already noted, helping to give uniform temperature distribution. During the higher temperature stages of the firing, therefore, it is desirable that most of the volatile matter from the coal should be burned among the ware so long as this can be done without detriment to the operation. In muffle kilns this combustion takes place in the kiln flues. The use of a deep fuel bed to provide carbon monoxide is also advantageous during this stage.

For each stage of the firing air control is very important and doors, covers or controllable secondary air flues are provided for this purpose. In exposed positions the provision of glut doors is an advantage to reduce wind effects and to allow the admission of primary air to be controlled.

Combustion conditions that require to be watched in order to attain economical use of fuel are as follows:

(a) *Water Smoking Period.* Unless the goods have been pre-dried before setting in the kiln, very slow rates of combustion are required during this period because the maximum safe rate of drying may be very low. Slow burning is obtained by maintaining a shallow fuel bed, which remains at a comparatively low temperature because the kiln draught is low and only a small proportion of the air passes through the fuel. The drying is carried out by heated air and some 10–15 times the air necessary for combustion may have to be drawn through the kiln in the earliest stages. This may be decreased as drying proceeds till only about three times the volume of air needed for combustion is admitted when the temperature of the goods reaches $100^{\circ}\text{--}150^{\circ}\text{C.}$ The most satisfactory conditions are obtained when the difference between the temperature of the waste gases and their dew-point is about 6°C. Artificially induced draught may be employed in the early stages to provide the required excess of air. The burner or fireman should avoid conditions that might lead to condensation of moisture in the cooler parts of the setting whatever the type of kiln, and this is controlled by the way in which the fires are gradually built up.

(b) *Rising Temperature Period.* In this period, chemical changes in the ware become important. Chemically combined water is removed and if carbonaceous material is present it must be burnt out. Iron compounds must be fully oxidised. A specific oxidising atmosphere is thus needed during this stage of the firing and the secondary air must be controlled.

Rates of firing depend on the time required to complete the oxidation before a temperature of 850°C. is reached in the kiln. The most efficient method of firing is that which avoids fluctuations in the temperature-time curve and undue excess of air. This can be assisted by giving the fireman a heating schedule. If a recording pyrometer is used, it is recommended that the ideal heating curve be drawn on the chart as a guide. Fluctuations may be unavoidable with intermittent firing and are not so serious under these conditions provided that black smoke does not issue from the kiln for long periods.

In the early stages fires should be built up gradually by small and frequent additions of fuel. Secondary air should be controlled to give approximately

8–12 per cent. CO_2 in the waste gases. The carbonaceous matter in the ware, which is an additional source of heat, requires air for its combustion. The minimum content of excess air, subject as stated before, to the limiting conditions of the process, gives in this as in other heating processes the maximum economy of fuel. The advantage of preheating the secondary air is all the more marked when an oxidising condition is required to be maintained in the kiln or oven.

At a suitable stage in the firing, when the temperature has reached a point at which combustion of the volatile matter can be ensured by the temperature of the ware, and where secondary air flues are not provided, another method of firing may be applied. This consists in feeding alternate fires, whereby hot secondary air from the intermediate fires can burn the volatiles from the freshly charged fires. It is most important to observe correct timing of the air controls in relation to the time of firing, and also to set the air controls correctly. The appearance of the smoke haze from the chimney stack is a useful indication of combustion conditions where more refined methods are not available.

Only a small proportion of pottery ovens work with an external stack, but observation of the absence of smoke at the outlet of the hovel or cone is possible if the ovens are not enclosed in a building.

(c) *High Temperature Period.* Although the rate of heating may generally be high at this stage, and may be consistent with economy, the technical features of the process determine the practice applied, and a soaking period may be necessary to ensure uniformity of temperature and the completion of the necessary chemical and physical changes in the ware, e.g. vitrification. With heavy firing, if oxidising conditions are required, local reduction may result, and ware be spoilt as well as fuel wasted. This is due to the difficulty of supplying sufficient air to burn the large volume of volatile products initially evolved. Small and frequent firing provides better conditions for the control of air.

In the normal method of firing, the glowing fuel is pushed down into the firemouth and the fresh charge of coal placed at the front and top of the fuel bed. With certain types of firing a steadier rate of evolution of volatile products may be obtained by using the coking method of firing. With this method the fresh charge is placed on a sloping refractory table above the main fire. When the next charge is due the partially coked fuel is pushed from the table on to the fuel bed proper and the fresh charge again fed on to the table.

In pottery practice the rate of heating the ware is slowest at the top temperature although the rate of burning the fuel may be highest. Soaking (i.e. deliberate holding at a constant temperature) is found to be necessary for most ceramic products in the first fire (biscuit) and is usual in the second or glost fire, but in the decorating kiln there is little or no soaking. In biscuit firing of pottery, fuel additions in the final period are usually heavy and it is generally necessary to maintain oxidising conditions if ware is not to be spoiled and fuel wasted.

Considering the oven or kiln as an isolated unit, i.e. in the absence of some form of recuperator, a high percentage loss of heat in the waste gases is the price which must inevitably be paid for the attainment of high temperatures in the setting, and the price is higher the larger the excess or deficit of air. Thus if the waste gases at the point of exit from the kiln are at a temperature of $1,000^\circ\text{C}.$, they will carry away 43 per cent. of the heat in the fuel (assumed to be coal with a calorific value of 14,000 B.t.u./lb.) even if combustion is perfect, i.e. no excess air. With 50 per cent. excess air they will carry away 60 per cent. of the heat in the fuel.

The important influence of secondary air control can be illustrated in the following manner. If the combustion temperature of the fuel is in the neighbourhood of $1,400^\circ\text{C}.$ and the finishing temperatures are in the range $1,000^\circ\text{C}.$ –

1,300° C., since the useful transfer of heat occurs only as long as the temperature of the heating medium is above that of the goods, a stage must be reached when the hot gases are imparting only a small proportion of their heat to the charge and the chimney loss must be necessarily high. If excess air is increased at this stage a serious loss of heat from the contents of the kiln must occur, since air picks up sensible heat from the already hot mass, which generally has a large surface exposed to the gases.

If, on the other hand, the excess air is reduced beyond the safe limit consistent with good temperature distribution, a reducing atmosphere causing unnecessary damage to the contents of the kiln may result. Spoilage of material and waste of fuel are thus largely governed by the manner of the air admission to the firing points and the general control of the kiln draught.

Summarising the requirements of fuel efficiency, as in other types of heating appliance, importance must be attached to correct selection and application of the fuel, combustion efficiency, draught control, the maintenance of correct temperature schedules and the uniformity of temperature distribution.

Continuous Kilns

Since the drying and preheating is performed by hot air from the cooling zone and hot kiln gases from the firing zone in continuous kilns, main considerations of the firing concern the conditions required in the firing zone. Thus once the required drying and preheating conditions have been determined, these stages of the heating are mainly controlled by fixing the lengths of the zones or parts of the circuit concerned. The drying and thermal requirements of the ware must be met as in intermittent firing, but because more control is usually obtainable much faster firing schedules are usually permissible.

Although most of the heat is recovered from the kiln gases and excess air does not involve the high losses found in intermittent practice, heat losses from these sources are not negligible and warrant some attention. Waste gases should not pass to the stack at temperatures above 100°–150° C. unless high draught is required and fans are not available. When fan draught is used waste gas temperatures need not exceed 60°–70° C. Heat losses due to excess air involve losses proportional to the waste gas temperature and the excess air present. The influence of excess air is most marked in the firing zone. Heat distribution in the whole circuit is influenced by the firing conditions used and by the rate of fire or car travel, and conditions in forward zones may have to be altered when these factors are varied. These alterations are mainly effected by adjusting the draught balance.

The firing proper must be considered in relation to the type of kiln employed. Car tunnel kilns in particular are amenable to continuous firing with solid fuel mechanically fed. But solid fuel firing is being progressively replaced by gas. Firing conditions are easily controlled. Since the tunnel is of small cross section, uniformity of temperature distribution is fairly quickly established. The main requirements are: correct draught balance; avoidance of undue excess air, particularly in the firing zone; and adjustment of the rate of car travel, of setting, and of flame or firing conditions, to provide uniformly fired products. Typical continuous kilns are shown in Figs. 10–12.

With top-fired Hoffman and transverse arch kilns most efficient firing conditions are obtained when small dry coal is fed continuously so that much of the combustion may be completed before the coal reaches the kiln floor. Thus, when mechanical stokers are not used, there should be very frequent additions of fuel at not more than 15-minute intervals. Air control is again important and draught requires special attention. Other factors which influence the firing

concern the type of setting employed, the number of cooling chambers and the number of forward chambers in the circuit.

The special requirements of grate and fender fired kilns, such as the Belgian and transverse arch chamber types, mainly concern control over combustion rates obtainable. The draught in the firing zone must be adequate to draw the maximum required amounts of primary air through the fuel bed without involving undue excess of secondary air in the chambers. For this reason the fuel bed must have a low resistance to air flow. Graded coals are therefore used and since the grates cannot be cleaned during the firing the coals should have low ash content. Generally coals of $\frac{1}{4}$ –1 inch size are suitable for fender firing and coals of 2–3 inches size for the firing of Belgian kilns. Good forward heat should be aimed at so that the minimum amount of coal is needed to reach the finishing temperature. Frequent firing at 15–20-minute intervals is again desirable, and a thin level fuel bed should be maintained. Long flame coals are specially desirable because the whole of the chamber must be uniformly heated by coal fed to each grate, the distance between grates being 11–15 feet.

Different methods of firing car tunnel and annular tunnel kilns are used in the pottery industry. Contamination due to the effect of atmosphere is overcome either by muffle heating or firing in saggars, by the choice of suitable fuel or by electrical heating. Counterflow types of continuous kilns are also employed. With open-flame heating, producer gas, town gas or oil firing provides conditions which are readily controlled, and once the air requirements have been properly adjusted to give satisfactory combustion conditions only minor adjustments are required. With these fuels multiple burners may be used to increase the uniformity of heat distribution. Although costs are high, electrical heating offers advantages, and in particular thermostatic control over finishing conditions is readily applied. For muffle firing the air admitted to the firing zone need not much exceed theoretical requirements.

SETTING OF WARES IN KILNS

The arrangements of the ware in intermittent kilns, in chambers of continuous kilns, or on the bogies or moving hearth of car tunnel or annular kilns, is equivalent in its effect on fuel consumption to the loading of other types of heating appliances. The material to be heated has thermal properties of the same order as the brickwork used in the construction of the heating chamber. This means that rates of heating are necessarily low and accordingly the character of the setting is critical in permitting a suitable circulation of hot gases, and at the same time giving an optimum rate of heat penetration in keeping with the technical requirements of the process worked.

The hot products of combustion are capable of a rate of heat release to the contents of the heating chamber which is very much higher than the capacity of the material heated to absorb it. The character of the setting is therefore an important factor in the determination of efficiency. Specification of the optimum setting density for all materials fired in the different kilns is not possible here because of the variable requirements. In general, however, ware which is not pre-dried before setting in the kiln, or ware containing much carbonaceous matter must be set more openly than other green products.

In pottery firing a special problem concerns the relative efficiency of placing in saggars or firing in muffles, where contamination with sulphur gases must be precluded. Much empirical work has been carried out on problems such as these, on methods of setting, and on setting density, but further research is required to determine optimum conditions. The question is important because fuel consumption, throughput, uniformity of treatment and of heat distribution, may be greatly influenced by the setting.

FACTORS AFFECTING FUEL EFFICIENCY IN KILNS

The main factors affecting fuel efficiency in kiln practice are:

- (a) Control of air to meet combustion requirements and the special requirements of the ware.
- (b) The suitability of the fuel or adaptation of firing methods to suit the fuel which is available.
- (c) Maintenance of the shortest safe firing schedules and obtaining the maximum throughput from the plant. In this connection as much of the production as possible should be fired in continuous kilns when they are available.
- (d) The use of optimum setting density for the goods fired.
- (e) Control over the firing; this includes methods of "baiting", i.e. feeding the fuel, temperature and draught control.
- (f) The use of insulation and attention to structural features.

The dimensions of firemouths, grates, fire arches, gluts and other pertinent structural features that may influence the flow of hot gases all fall into the class of controllable factors, which at rebuilds can be adjusted to improve performance. They all depend upon the process operated and local conditions. No hard and fast rules of a general type can be laid down beyond an elaboration in detail of the principles already outlined, in particular in the chapters on combustion, heat transmission, the flow of gases, and refractory materials. For details of structural technique reference should be made to specialist volumes and technical journals.

Heat insulation of kilns and ovens has made contributions to the more efficient use of fuel. Heat-insulating materials may be used both as external layers and in the internal structure. Thus the use of hot-face insulating material in intermittent kilns as an inner lining and for crowns, together with insulation beneath the kiln floor, has resulted in a considerable reduction of loss of heat in the structure, in greater uniformity of heating, and in reduced duration of firing for those wares which may be fired without harm at increased rates. There is a limit to the practicability of using hot-face insulating materials for the highest temperatures. Saving in fuel amounting to 10 per cent. and upwards of the original fuel consumption have been claimed as a result of the use of such materials.

Attention is directed to the value of measurements of temperature, draught and to gas analyses, as well as records of all factors concerned with firing. Measurements and records frequently enable fuel savings to be made because they emphasise the importance of economy to the firemen and provide objectives to be attained.

FURNACES AND FURNACE CONTROL IN THE GLASS INDUSTRY

In the manufacture of glass, various types of furnaces and heating appliances are used for the melting, reheating and annealing, etc., of the glass and glass ware, but by far the greatest amount of the fuel used is that for heating the melting furnaces. There are two general types of these, known as *pot furnaces* and *tank furnaces*.

POT FURNACES

Pot furnaces are used where it is necessary to produce a wide variety of glasses in small quantities, or where it is essential to protect the molten glass from furnace gases. A pot furnace consists of a combustion chamber of a high grade refractory such as sillimanite, arched with an insulated silica crown, and is usually recuperative rather than regenerative. The furnace is worked continuously and fifteen years of operation without repair is possible.

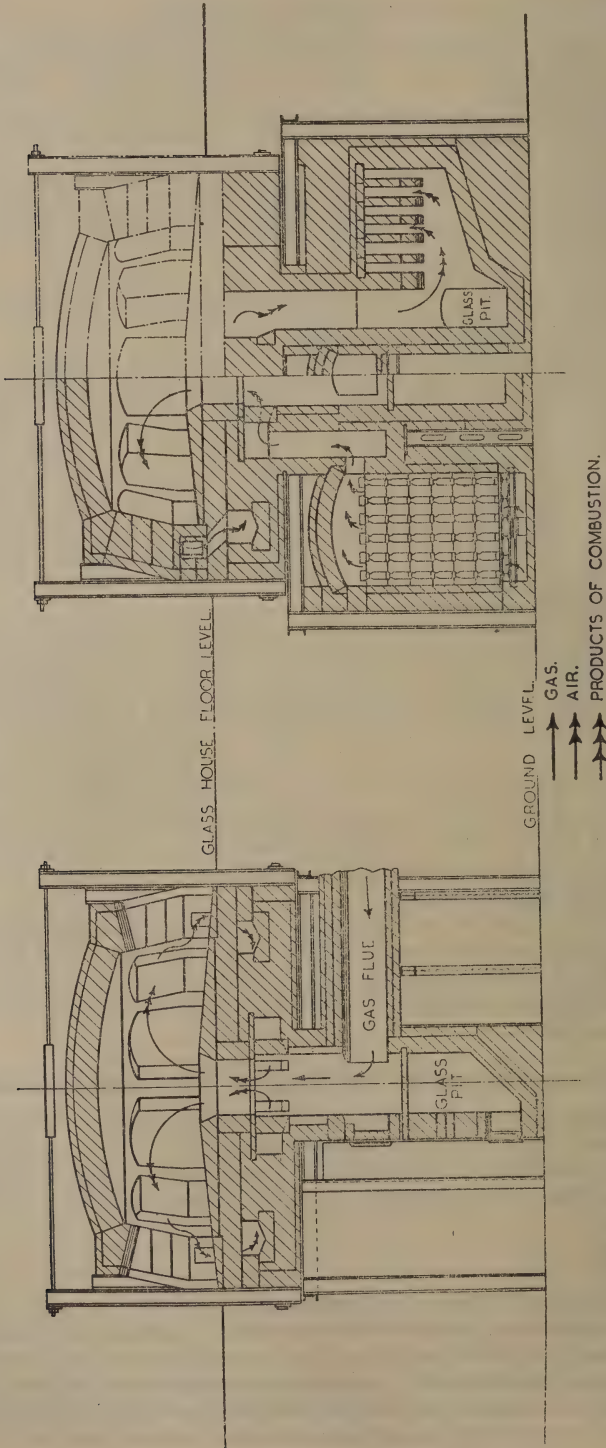


FIG. 13. Recuperative pot furnace for glass making.

In addition to the circular pot furnaces of the type illustrated in Fig. 13, containing eight to twelve of the pots in which glass is melted, there are many variations in both size and shape, but the general principles of operation are similar. One-pot or two-pot furnaces are becoming popular for certain applications, and small tanks of about one ton capacity are in use, which combine some of the flexibility of the pot furnace with some of the efficiency of the tank furnace, and have, naturally, some of the disadvantages of both. Pot furnaces for the manufacture of special types of plate glass are usually rectangular in shape, having a row of pots down each side, and are mainly regenerative, end ports giving a sweep of flame down the whole length.

The most common method of firing is by producer gas, town gas or coke oven gas, but built-in producers are sometimes used; oil firing has become popular in recent years.

The pots, hand-made of pot-clay, are about four inches thick, tapering to two inches in the hood and are replaced as they become corroded by the solvent action of the molten glass. They may hold 10–30 cwt. of glass and may be open-topped, or hooded with a mouth at the front.

Pre-heating the Pots

This is done in a small auxiliary furnace known as a pot arch. The pots are placed in the pot arch in the green (unburnt) state and are fired at 1,100° C. to 1,400° C., according to the practice of the user. They are transferred to the main furnace at the maximum temperature. The pot arch is a simple type of furnace commonly fired with coke-oven, producer, or town gas. The modern types are usually constructed almost entirely of insulating refractories, and success has been achieved with metal recuperators. When fitted with fanned secondary air and an air-gas proportioning valve, high standards of control are achieved. An arching period of five days, to a maximum of 1,150° C., is normal. Where higher temperatures are desired the pot arch has to be constructed of suitable materials, the hot-face insulation being replaced by fire-bricks. Many users prefer to use a hot-face insulated pot arch for reasons of fuel economy and complete the firing to higher temperatures by allowing the pot to stand empty in the main furnace for about 24 hours.

Furnace Operation

The hooded pots are charged, usually by hand, with a mixture of *batch* (raw materials) and *cullet* (broken scrap glass) and stoppered up. A period—widely variable according to the type of glass—elapses while the rge chapartly vitrifies and subsides, and a second and sometimes a third charge is then added. When the charge is fully converted to molten glass a further period is allowed for the escape of gas bubbles, and when clear, the stopper is gradually eased to allow the glass to cool to working temperature. The glass is then skimmed and is ready for use. This process is known as “founding” glass.

There are two main systems of operation :

1. All pots are filled in the evening, and the furnace temperature is controlled so that all pots are ready by morning and are worked out during the day. Open pots are desirable for this system as the heat transfer to the glass is more rapid than with a hooded pot.
2. Each pot is filled in turn as it is worked out so that the furnace is continually producing molten glass. This system is used in the hand-made crystal glass industry, where the high quality of glass demands a long refining period.

The design of the pot furnace lends itself to modern fuel saving techniques such as substantial insulation and intelligent instrumentation, and great strides

have been made in this direction. The waste gases usually leave the furnace at temperatures about $500^{\circ}\text{C}.$; it is therefore difficult to use them for steam raising, though it has been done. Recent installations of heat exchangers to produce hot air for space heating have been quite successful.

The table below gives some indication of the normal working conditions of a pot furnace, the figures being taken from information obtained by teams from the Department of Glass Technology, Sheffield University, when surveying the heat distribution in pot furnaces.

Recuperative Furnace—(10 years old)

Capacity: 10 covered pots each holding 12 cwt. of lead crystal glass.

Fuel: Heavy oil (low pressure burners).

Fuel Consumption: 15.7 gal./hour.

Temp. of Combustion Chamber: $1,350^{\circ}\text{C}.$

Excess Air in Combustion Chamber: 3 per cent.

Temp. of Waste Gas leaving Recuperator: $590^{\circ}\text{C}.$

Recuperator Efficiency: 81.4 per cent.

"Furnace efficiency" figures for pot furnaces can be very misleading, since all the glass produced at the end of founding is not immediately formed into glassware. A pot is often kept at working temperatures for a period exceeding its founding period, and the working period can, for example in the case of skilled glassmakers making high quality wine glasses, be as much as four times the founding period. On the other hand, when the furnace is being used for production of, say, bottles, at high speeds, the working period is substantially reduced. Moreover, the radiation loss from the open pot mouths during the working period is very great and, under continuous working conditions, can be as high as 12 per cent. of the total heat losses from the furnace structure.

Thus the efficiency of the furnace is dependent more on the type of work produced than on the design and operation of the furnace. For this reason users of pot furnaces do not use an overall efficiency figure in assessing their furnaces, but prefer to study the information that can be obtained regarding the relative heat requirements of different parts of the furnace system.

Maintenance of Pot Furnaces

In order to ensure the efficient use of fuel in pot furnaces the following points should have constant attention :

1. Correct combustion conditions.
2. Careful sealing of inspection stoppers, particularly in downtakes.
3. Minimum practicable stack draught.
4. Sound recuperator tubes. Excessive cleaning may open up joints and, by air inleakage, do more harm than good.
5. Clean glass pockets. A generous layer of sand on the bottom facilitates cleaning.
6. Regular inspection of downtakes and recuperators.

TANK FURNACES

A tank furnace consists essentially of a bath, the bottom and sides of which are usually constructed of suitable refractory material in the form of large blocks. In some furnaces, however, the bottom and, in furnaces for melting coloured glass, the lower part of the sides are of brick construction. Rising above the walls of the tank proper are the upper walls with ports for entrance of fuel and air, and exit of waste gases, and covering the whole is an arch or crown. This superstructure is usually made entirely of silica brick, though blocks of sillimanite or other highly refractory material are now being used for parts of the port openings and upper side walls.

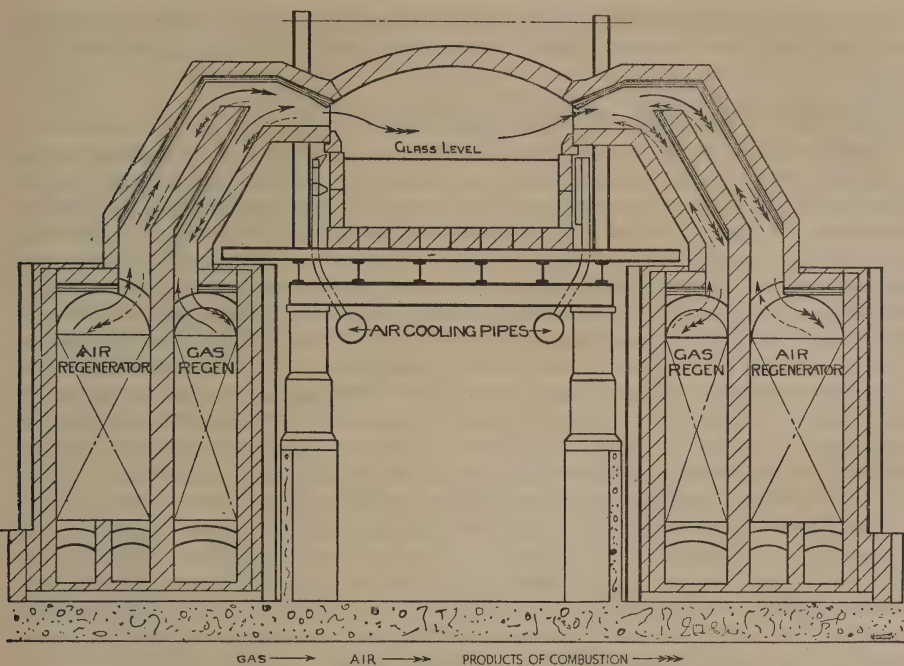


FIG. 14. Cross-flame regenerative glass melting tank, fired with producer gas.

The tank furnace is heated by a flame or flames projected either across the width of the furnace (cross-flame firing) or down the length (end-firing). The type of burner and the means of supplying the air needed for combustion depend on the type of fuel used. In all but some very small furnaces as much as possible of the heat in the waste furnace gases is recovered in recuperator or regenerator chambers, the recovered heat being used to pre-heat the air, and the producer gas where that fuel is used. The modern continuous tank furnace is usually of the cross-flame regenerator type, recuperators being employed more generally for smaller furnaces.

The use of electricity for melting or for assisting in melting glass in tank furnaces is coming rapidly into use in some countries. In Britain, electric heating is being used in a limited number of furnaces for "boosting" the heating obtained by more normal methods.

A cross-section of a typical cross-flame regenerative tank furnace is shown in Fig. 14. The tank is divided transversely by a double-walled bridge into two compartments, the larger, to which the batch is added, being termed the *melting chamber*, and the smaller and cooler, from which the glass is withdrawn, the *working chamber*. These two compartments are connected by relatively small channels usually near the furnace floor.

Large tank furnaces for sheet or plate glass are often divided into two compartments by a shadow wall or flying arch: cross-flame firing is invariably used in the melting end.

"Day" or intermittent tanks are usually small. They normally have no bridge, and their operation resembles that of pot furnaces.

Most glass bottle tank furnaces in Britain are 30–60 ft. long and 2–4 ft. deep, and have a capacity of 100–400 tons of glass, the amount of glass melted per day being usually of the order of one ton for each 7–15 sq. ft. of the surface

of the glass in the melting chamber. They operate continuously 24 hours a day, for periods of ten to thirty months or more, until major repairs are required.

GLASS MELTING TANK FURNACE OPERATION

Charging the Furnace. The mixed batch, comprising sand, limestone, soda ash, etc., and usually including a proportion of cullet, may be introduced into the furnace by (a) hand-shovelling, or by (b) semi-automatic or (c) fully-automatic means. In (a) and (b) the batch is introduced at frequent intervals in amounts consistent with the rate of withdrawal of the glass from the furnace. In (c) the feed is similarly arranged but is continuous. Completely automatic methods allow the furnace to be kept closed, reducing loss of heat and temperature variation, and making for better fuel efficiency. Fully automatic methods also permit better control of glass level, and are believed to assist in preventing batch being carried into the regenerators. Glass batch is dusty and avoidance of choking of the regenerators by the dust is a matter for special consideration in the design of glass tank furnaces. Some modern methods of automatic batch feeding bring the batch in a "blanket" or ribbon through a lower temperature zone where a preliminary fritting occurs.

The Melting and Refining Process. Glass melting in tanks may be considered in three stages. 1. The batch is pushed into the furnace, floating on the bath of molten glass, and melted to a frothy glass. 2. This glass is refined by *holding* it at a temperature sufficiently high to get rid of gas bubbles and also to allow diffusion, etc., to render the glass homogeneous. 3. The glass flows to the cooler working end for temperature adjustment and delivery to the machines, or for gathering for hand-operation.

The first two stages just described are carried out in the melting chamber of the furnace, and as refining requires the longer time and the higher temperature the major part of the space must be reserved for it. This means that unmelted batch must be confined to a small space at the batch entry end of the furnace, and about three-quarters of the glass surface in the melting end should be left free for refining, and this part of the furnace should be the hottest.

The appearance of *seed* or small bubbles in the glass withdrawn is frequently an indication that the furnace temperature is too low, or the glass is being withdrawn too rapidly. The correct furnace temperature is the lowest that will give glass of the required quality.

Conversion of Glass into Glassware. The glass is supplied from the working end to one or more operating units. The forming of the glassware may be carried out by hand-operation only, by hand-gathering with machine-forming, or by fully-automatic machines. For the latter, the glass is usually delivered to projecting chambers, of various types, in which its temperature is precisely adjusted to and controlled at the required value.

ANNEALING FURNACES (LEHRs)

These are long narrow structures of tunnel formation through which the glass or glassware passes more or less continuously. Heating facilities are provided in all lehrs, the heat being applied either directly or through a muffle system. The source of heat may be any type of fuel. Most modern lehrs are constructed almost entirely of metal, are well insulated, and use a mattress-type of conveyor; some lehrs require no fuel or energy for a wide range of operating conditions, relying entirely on the heat in the glassware as it comes from the machine.

The object of annealing is to avoid setting up in the glass, by too rapid or

uneven cooling, stresses that might cause or increase tendency to fracture. In the first part of the lehr the glass is maintained at such a uniform high temperature as is necessary to relieve the temporary stresses caused by the processing. It is then cooled so slowly that no new stresses are set up. This is continued to a temperature below which, due to the rigidity of the glass, no permanent stresses can be set up. From then onwards the glass is cooled down nearly to atmospheric temperature, as quickly as necessary, or as quickly as it will stand without fracture due to the temporary stresses. This cooling is assisted by controlled air currents passing up the lehr from the cold end towards the hot end.

When articles of different shapes, sizes and thickness have to be annealed together, compromise annealing schedules have to be used. Both quality of annealing and fuel efficiency suffer in such circumstances. The following general rules may be given for satisfactory lehr operation:

- (1) The ware should be put in the lehr as quickly as is possible without risk of deformation of the ware.
- (2) It should be packed as tightly and uniformly as possible, but not so tightly that the articles touch or might touch owing to vibration, etc.
- (3) Lehr doors must fit tightly, and be kept closed as much as possible, and no air should leak in from below. Draughts are the curse of all lehrs.
- (4) Air circulation for accelerated cooling should be carefully controlled, to obtain proper temperature distribution.
- (5) If it is evident that bottoms of glassware have not been well annealed, draughts should first be looked for, then the lehr should be examined by means of a travelling thermocouple for places where a sudden temperature drop might occur. Drum heat and burner regulation should be examined and readjusted to give the desired cooling curve.
- (6) Instruments must be kept in perfect condition and be checked at regular intervals.
- (7) The lehr designers' instructions should not be forgotten or discarded.

FUELS USED IN THE GLASS INDUSTRY

General Review;

Three types of fuel are mainly used for heating the furnaces, viz.:

- (1) Producer gas,
- (2) Coke oven gas or town gas,
- (3) Oil.

Electricity is used to a limited extent, its economic use in Britain (as mentioned earlier) being probably limited to auxiliary heating to assist the main fuel.

In common with all large furnace operations, the objects of efficient fuel utilization are to ensure that a constant quantity of fuel of definite quality shall be delivered to the furnace in unit time, and that such fuel shall be supplied with the required amount of highly preheated air to ensure complete combustion in the melting chamber.

The factors affecting this are:

- (1) Type of fuel: size and grading.
- (2) Port design: $\left\{ \begin{array}{l} \text{cross-sectional area,} \\ \text{angle of inclination,} \\ \text{point at which fuel and air meet,} \\ \text{mixing characteristics.} \end{array} \right.$
- (3) Combustion space characteristics.
- (4) Regenerators: $\left\{ \begin{array}{l} \text{height and width,} \\ \text{type and height of packing.} \\ \text{reservoir between packing and top of chamber.} \end{array} \right.$

- (5) Insulation of furnace superstructure, ports and port stacks.
- (6) Correct draught and furnace pressure.
- (7) Minimizing air leakage into furnace and regenerators.
- (8) Suitable control instruments and intelligent interpretation of results.

INDIVIDUAL FUELS AND CONDITIONS OF USE

Producer Gas. The gas should have as high a CO content as possible. It should be of consistent quality and quantity, and be delivered to the furnace at as uniform a pressure and as high a temperature as possible. Regular gas analyses should be made, an experienced operator being able to determine roughly the quality of the gas by a CO₂ determination only. For good quality gas this should be 5 per cent. or less. Complete analyses should be made at regular intervals, or continuous methods of gas sampling may be employed apart from the CO₂ tests, and the calorific value may be calculated from the results.

A recorder for the gas off-take temperature is recommended as being the most useful instrument for obtaining consistent gas quality under working conditions.

The pressure in the producer main should be known and maintained. Flues should be kept gas-tight, dust pockets adequate and regularly cleaned, and flues burnt out with a minimum delay to the working programme. Many firms have eliminated periodical burnouts by installing large gas mains and using steam lances during normal operation of the plant. Automatic steam-operated dust and tar removers are now available.

Coke Oven Gas or Town Gas. This fuel presents ample opportunities for using control instruments, and full advantage should be taken of them. The set-up and interpretation of the results are as follows:

- (a) Recording pressure gauge on the mains.
- (b) Governors fitted to each furnace to reduce main gas pressure to that desired, and to eliminate pressure fluctuations in the mains. This gives a steady gas supply.
- (c) Orifice plates in individual furnace mains coupled to recorders and integrators. Gas flow is continuously recorded, and daily or hourly consumption figures are thus available.
- (d) Recording calorimeter. If the calorific value of the gas fluctuates, the gas flow can be altered to meet it.
- (e) Measured secondary air flow permits control of air to gas ratio.
- (f) Waste gas analyses should be consistently taken to ascertain that combustion has been completed in the furnace.

Oil Fuels. The use of oil fuels is discussed generally in Chap. 13. For information on oil burning relating directly to the glass industry see the bibliography^{9,10} at the end of this chapter.

For efficiency and fuel economy, high-pressure atomizing burners should in general be installed. A minimum of air should be used for atomization in order that the maximum quantity of secondary air can be pre-heated. In pot furnaces with a large combustion space relative to that occupied by the pots, low pressure burners, while less, giving poorer fuel efficiency, possess advantages over the high pressure system.

In cross-flame furnaces, where periodical reversal occurs, arrangements are often made whereby the burners are automatically swung out from one set of ports as the burners on the opposite set swing into position. The burners may be introduced through the back of the ports, or over the port mouth, or through the sides near the furnace wall, or underneath the ports, just above the glass surface. They should be so arranged that undue wear of the ports

is avoided, and the full heat of the flame developed where it is desired, i.e. in the furnace and not in the ports.

With oil firing, the deposition of carbon can be rapid if the oil flame, in its early stages of combustion, impinges on a cooler surface. This deposition may occur on port sides with incorrectly located burners or may occur inside the furnace. Poor atomization and/or wrong location of the burner is usually the chief cause of the trouble.

In the operation of some of the larger glass-making machines an auxiliary furnace, known as a revolving pot furnace, is contiguous with the main furnace, glass flowing from the main furnace to the auxiliary. Precise temperature control is essential, and the temperature of these auxiliary furnaces is maintained to an accuracy of $\pm 5^\circ \text{C}$. by controlling pyrometers which, through a relay, regulate the oil supply to the combustion zone.

Air Supply and Control. It has been shown¹¹ by research on air flow to glass tank furnaces that air and gas entering a regenerator do not necessarily distribute themselves in the same ratio to all ports; sight holes for the easy examination of the flames from each port are thus an advantage.

Some works have used the difference in cross-section of air or gas flues and the regenerator as a rough orifice plate, and by coupling up an inclined manometer to read the difference in pressure between air and gas flues and the regenerator have obtained useful control of air and gas flow through the regenerator. Such methods are not accurate but by systematic observation they do give the furnace operator additional data on his furnace and help in efficient operation.

The air supply has also been controlled in some plants by using dampers in each individual port, but owing to mechanical difficulties this practice is not generally satisfactory. Control is, therefore, best effected by careful adjustment of the air valve and by so designing the relative widths of the uptakes to each port that the correct longitudinal temperature distribution is obtained. Air shortage can be overcome by installing a fan on the air valve, but very close control is required.

The percentage of excess air should be a minimum consistent with correct length and type of flame in the melting chamber.

THE CONTROL OF GLASS FURNACE OPERATION

Both chemical and physical methods are widely used, the former including analysis of fuels and waste gases, the latter temperature and pressure measurements.

CHEMICAL METHODS

(1) *Analysis of Fuels.*

- (a) coals are examined for their suitability as producer fuels;
- (b) liquid fuels are tested for viscosity and sulphur and water content, and for calorific value.

(2) *Analysis of Waste Gases*

Air Supply. Systematic waste gas analyses are the usual method of checking the adequacy of the air supply. As CO_2 is liberated from the melting batch, due allowance must be made for that factor. The following formula may be employed to determine the amount of CO_2 from the batch:

$$x = \frac{100}{100 - y} \left[A + C + \frac{y}{21} (B - 0.395C) - y \right]$$

where x = percentage CO_2 in waste gases due to batch

y = „ CO_2 in products of perfect combustion (i.e. maximum percentage of CO_2)

A = percentage CO_2 in waste gases as analysed

B = " O_2 " " " "

C = " CO " " " "

The true percentage CO_2 content of the waste gases is $\frac{100(A-x)}{100-x}$.

$$\text{If } C = \text{zero, then } x = \frac{100}{100-y} \left[A + \frac{By}{21} - y \right].$$

The point of sampling the waste gases is of vital importance because in-leakage of air is, in many furnace structures, sufficient to lull an unskilled operator into a false sense of security regarding the air supply. The sampling should be done through silica tubes, an auxiliary flowing stream of waste gas being tapped into the sampling apparatus, and the sampling point should be *as close to the melting chamber as possible*. A port close to the bridge should be used in preference to one near the melting batch piles.

Traces of CO are not inconsistent with high furnace efficiency, particularly where the sampling position is near to the furnace and the excess air is low, i.e. of the order of 7-10 per cent.

PHYSICAL METHODS

(1) Temperature Control

(a) *Temperature Control of Furnaces.* Pyrometers of the radiation type or rare metal thermocouples, correctly sheathed, and suitably positioned are used for recording the furnace temperatures in the working and melting chambers of the furnace.

Open-scale recorders of the potentiometric type are widely used. These instruments can give reasonably precise information of any fluctuations in the furnace temperature, and if calibrated so that the whole scale is covered by the short temperature interval, $1,200^\circ\text{--}1,500^\circ\text{C}$. or $1,000^\circ\text{--}1,500^\circ\text{C}$. give a much more accurate and useful indication of conditions than instruments whose scale covers $0^\circ\text{--}1,400^\circ\text{C}$. With the more extended range small fluctuations are not readily seen and furnace control suffers accordingly.

In addition, optical pyrometers of the disappearing-filament type are commonly used as a means of obtaining an indication of the true furnace temperature inside the furnace. Regular readings are taken by sighting these instruments on to the bridge wall or on the glass surface while the gas is off during a reversal. These readings act as a check on the normal recorders.

Radiation pyrometers are often placed in the back wall of the furnace, and are sighted on to closed refractory tubes. They must remain in focus and be kept clean. Thermocouples usually occupy a central position in the crown in the melting and working ends of the furnace, and are mounted in special refractory blocks. All thermocouples should have compensating leads. Modern instruments have automatic cold junction temperature compensation.

Whatever type of pyrometer is used, it must be the slave and not the master of the operator. A pyrometer cannot indicate whether the furnaces are working satisfactorily or not; its main uses are:

- (1) To indicate to the furnace operator whether the temperature is steady, tending to rise or tending to fall.
- (2) To serve as guide if the necessity should arise for raising or lowering the temperature, this being judged by the condition of the furnace and the glass being withdrawn from the working end.
- (3) To provide information for all concerned with the operation of the furnace.

(b) *Temperature Control of Regenerators.* In some plants thermocouples are located in the regenerators, and reversals are made at intervals corresponding to definite temperature conditions in these structures.

Normally, however, reversals occur every half hour. With regenerative furnaces a steady rise and fall in the furnace temperature occurs, between certain limits, during each half-hourly reversal. This fluctuation does not occur with recuperative furnaces.

(c) *Temperature Control of Lehrs.* It is important to have a thermocouple and recorder for the point, within the lehr, of maximum temperature. An indicator giving temperatures at various points along the lehr is useful. The most important points are :

- (i) Just inside the front of the lehr,
- (ii) The point where slow cooling is expected to begin,
- (iii) The point where fast cooling is expected to begin,
- (iv) Near the outlet end of the lehr.

If difficulty arises with a lehr, the best method of examining it is by the use of a travelling thermocouple, made up of iron and constantan, or chromel and alumel and insulated with asbestos tubing or refractory beads. Generally a length of 30–40 ft. is sufficient. The thermocouple can be hooked to the conveyor, or weighted in order that it may travel through the lehr with the ware.

(2) *Pressure Control*

Dampers should be of a type which gives easy and precise adjustment. Where remote control is not used draught gauges should be so located that they can easily be read during damper adjustment.

Draught gauges should preferably be of the recording type and where over-ground metal flues are employed a piezometer ring should be used in connecting to the gauges. The draught tube should be placed between the chimney damper and the air valve, it being necessary to ensure that the air valve does not cause a large or variable drop, which, apart from other disadvantages, would introduce uncertainties into the draught readings.

The draught reading should always be as low as is consistent with satisfactory operation of the furnace, i.e. the adjustment should be such that a slight positive pressure is maintained in the furnace. Furnace pressures are frequently recorded continuously in a gauge connected by gas-tight tubing to a tube through the furnace crown, and they may be controlled by means of an automatic movement of the stack damper in response to a signal from the furnace pressure recorder.

MAXIMS FOR FUEL ECONOMY IN THE GLASS INDUSTRY

The following are maxims for getting good glass with good fuel economy:

- (1) Spread the batch well over the glass but keep it from floating too far forward.
- (2) Keep the melting end of the furnace at the temperature needed to make good glass, but not hotter.
- (3) Maintain a steady temperature with the help of a pyrometer, and make regular checks of the furnace temperature by the use of a disappearing-filament pyrometer, sighted on to a definite spot in the furnace, during gas reversals.
- (4) Use the correct amount of air, avoiding either too short a flame or the appearance of smoke.
- (5) Keep long even flames rolling close to but not touching the glass surface, and terminating before they quite reach the outlet ports.

- (6) Keep the stack damper as low as possible without causing excessive stignout.
- (7) Avoid leaving unnecessary holes open around the furnace.
- (8) Stop up immediately any cracks appearing in the superstructure of the tank or regenerators.
- (9) Use an efficient regenerator system, of adequate size and correctly packed.
- (10) Use insulation wherever the condition of refractories permits.
- (11) Use cooling only to maintain key refractory positions for an economically long life, endeavouring to reconcile long life with fuel efficiency.

ASSESSMENT OF THE EFFICIENCY OF TANK FURNACES

In order to keep a careful watch on the fuel efficiency of furnaces it is necessary to consider the quantity of fuel used and the total glass output. Unfortunately, it has been a custom for many years to express the fuel performance of a furnace in terms of the weight of fuel used per ton of glass melted. This is a ratio of great practical importance, but for the assessment of *thermal* efficiency it is misleading because the greater part of the fuel (80–85 per cent.) is used not for melting glass but for keeping the furnace hot.

The Furnace Committee of the Society of Glass Technology developed a method¹² for assessing the performance of all sizes of furnaces, working under greatly varying conditions of output, fuel type, and operating temperature. The performance is expressed as the number of B.t.u. required per second to maintain 1 sq. ft. of the furnace area at a standard temperature 1,400° C., under no-load conditions, reference being made to a furnace having a standard area of 600 sq. ft. The performance figure is given by the formula:

$$Q=0.026\left(\frac{CH}{AK_A K_T}-\frac{Wc}{AK_A}\right)$$

in which

Q=Quantity of heat required per second to maintain
1 sq. ft. of glass surface at 1,400° C. B.t.u./sq. ft.sec.

C=Total quantity of fuel consumed in the furnace per
24 hours tons/24 hrs.

H=The net heat content of the fuel B.t.u./lb.

A=Total area of the glass in the melting and working
portions of the furnace exposed to the crown when
the furnace is new sq. ft.

W=Weight of glass discharged from the furnace per 24
hours tons/24 hrs.

c=Quantity of heat required, at the reversing valve of
the furnace system, or at an equivalent position,
to melt the raw materials needed to yield 1 lb. of
glass, and to raise its temperature to 1,400° B.t.u./lb.

K_T=Numerical correction factor to be applied when the
furnace, as a whole, is working at some tempera-
ture other than 1,400°

K_A=Numerical factor to enable correction of furnace
area to be made to the standard of 600 sq. ft.

In the case of producer gas firing, the quantity H, net heat content of the fuel at the furnace valve, is usually unknown. H is then usually taken as 0.8 of the net calorific value of the coal charged into the producer.

The values of the factors c, K_T, and K_A have been tabulated and can be found in the paper referred to.

As a result of applying this formula to a large number of tank furnaces melting colourless glass, furnaces with Q less than 5 are regarded as good, between 5 and 6 as fair, between 6 and 7 as poor, and over 7 bad. The regular use of this formula enables a check to be kept on overall furnace operation. As frequently as fuel consumptions are recorded, the performance for each furnace should be calculated and compared graphically with previous values. Excessive use of fuel is indicated by an increase in the performance index; a slow steady rise normally results as the furnace gets older.

The British Standard Test Code¹³, B.S.1312, provides instructions for carrying out tests of the performance and efficiency of regenerative tank furnaces for melting glass, either to check conditions that may form part of a contract between furnace builder and user, or for a full evaluation of the performance of all sections of the furnace system.

REHEATING FURNACES

Reheating furnaces are used for the heating of material for fashioning, and are accordingly confined generally to the metallurgical industries. They are found in rolling mill, forge, press shop, and other workshops where heating prior to shaping is required. Reheating may be effected in various stages, in each of which the function of the furnace may be different, and special types of furnaces for the specific stage of the heating may then be used; e.g. pre-heating furnaces prior to transfer to another furnace for the main stage of heating, wash heating for quick reheating of hot blooms already partially fashioned, sheet and pair furnaces in connection with the rolling of sheets, and soaking pits for finishing the heating of already hot ingots for rolling.

They may be operated intermittently or as batch furnaces in which the heating of the material is carried out in successive charges, or on the continuous principle in which the charge is moved through the furnace by means of a suitable mechanism, such as a pusher, conveyor, bogie carriage, car bottom or rotating hearth.

All types of fuel are used, and the methods of their application vary widely according to the type of material involved and availability of fuel and shop layout. The extent to which scientific design of furnaces has progressed varies considerably; it is particularly advanced in batch and continuous reheating furnaces. Knowledge of the development of the flame, the subsequent heat release and condition of heat into the charge is based partly on empirical methods. Thus, while the heat put into the furnace may be accurately known, the temperature of the products of combustion and their radiant properties, influenced as they are by the aerodynamic conditions of the burning appliance, cannot be predicted. The turbulence produced between the air and fuel streams determines both the temperature and emissivity of the products of combustion and, therefore, the heat transmission over particular areas of the furnace. Either luminous or non-luminous flames can be used (See Chap. 9.)

METHODS OF FIRING

Most of the factors relating to the problems of combustion and heat transmission have already been mentioned, and it remains to discuss special points relating to the various fuels.

COAL FIRING

(i) *Hand-fired Furnaces.* Both natural and forced draught are used. The coal burns as it would on a boiler grate, with the difference that larger sizes of fuel and thicker fuel beds are customarily used. Rates of combustion on the grate fall within the range of 10–20 lb. per square foot of grate area per hour. Long flame, free-burning coals are preferred. All the air may be supplied as

primary air through the grate. Secondary air may also be used with advantage, but its use requires attention to distribution and control, since the volatile content of the flame varies as each charge of green fuel burns off. Local jets of excess air may cause spoil material.

With natural draught the main control of the furnace operation depends upon damper adjustment. Dampers should always be kept in good repair and be capable of fine adjustment since the difference between satisfactory and faulty operation may depend upon the possibility of working to $\frac{1}{16}$ inch w.g. of furnace draught or even less. The level of the grate in relation to that of the hearth and the bridge wall is important in assisting uniform heating. The lower the grate the higher the gas pressure at the bridge wall, and the easier it is to obviate air leakage at the hearth level.

The control of heating in the furnace is more effective when the fire-grate is enclosed and positive draught applied.

Fans are preferable to steam jet injection, since the steam consumption may be as high as 1 lb. of steam per lb. of coal, and worn or wrongly centred jets are particularly wasteful. (See Chap. 11.) Firebar design repays investigation. A device of using cast angle bars resting in grooves on a bearer sloped and admitting of the use of a trickle of water along the bars has been used with success in preventing clinking. In large coal-fired furnaces, in order to obtain uniform temperature and adequate fuel bed control, it is often necessary to use several separated grates rather than one large one.

(ii) *Built-on Producers.* Self-contained producers built on to the furnace chamber vary in design from what is simply a sloping grate fired through a door placed above the top of the grate to a static producer with the normal type of tuyère using steam-air blast and a charging hopper. Secondary air is necessary, and it may be pre-heated. Many special types of grate have been applied to assist in breaking up clinker and cleaning the fires. The choice of fuel used and the technique of operation resembles in essential elements the practice for normal producer operation (Chapter 18).

(iii) *Mechanical Stokers.* Underfeed and sprinkler stokers are used for reheating furnace operation. Temperatures in the combustion chamber are necessarily high and the conditions may cause parts of underfeed stokers to be burnt out unless the proper precautions peculiar to the stoker are observed. For the same reason the backplate and driving shaft of the sprinkler mechanism in the sprinkler type should be water-cooled.

It has been found possible to operate mechanical stokers in reheating furnace practice with almost ideal combustion conditions, and accordingly they can show an economy over hand firing. But it must not be presumed that a mechanical stoker will necessarily show this economy, unless intelligence is applied in its handling. With unskilful operation it can be as wasteful as hand firing.

Mechanical stokers are usually operated with positive draught and secondary air may be applied provided a sufficiently thick fuel bed is carried. They are also capable of being operated in conjunction with automatic furnace control, either from a pyrometer, registering the temperature, or a draught controller.

(iv) *Pulverized Coal.* Pulverized coal firing has been successfully applied to reheating furnaces of both the batch and continuous types in a wide range of practice. Some of the advantages which gas and oil have over coal on the grate are also offered by its use. These advantages include control of combustion, as regards both rate of firing and fuel-air ratio, and quick heating from a cold start. The equipment used is described in Chapter 12.

Fineness of grinding is a question of compromise between economics and the technical requirements of each individual problem, but the technique of

grinding and burner design has advanced to the stage at which the use of powdered fuel in small furnaces for the heating of billets for drop stamping is a practical and economic success.

In burner design it should be borne in mind that powdered coal will not burn in the open air, whereas well-atomized oil, with some difficulty, and gaseous fuels, readily, do so. Accordingly the flame should be surrounded by brickwork at its root. The design of the burner and combustion chamber is a specialist's problem, but the simplest types of burner are usually the most successful.

The powdered coal flame is generally one of high calorific intensity, and therefore in general, with suitable safeguards against local overheating, applicable to reheating furnace practice. Flame intensities and flame length can be varied with powdered coal in very much the same manner as with oil and gas.

The action of powdered coal on brickwork varies greatly with the composition of the ash and with the furnace temperature. Special attention must be devoted to selection of refractory materials and the design of flue offtakes and waste gas ducts. Ready accessibility for cleaning is essential.

In bunkers provision is necessary to safeguard against fires arising from autogenous combustion. Carbon dioxide may be used as the smothering agent. Coal dust explosions are rare in modern pulverized coal plants.

GAS AND OIL FIRING

The characteristics of gaseous and liquid fuels have been discussed in other chapters. They are applied in every known form in reheating furnaces and their methods of application are too numerous to deal with in an adequate descriptive manner within the compass of this volume. Their main inherent advantage lies in the effectiveness with which the combustion conditions may be controlled and the heat distributed in the furnace.

AIR PRE-HEATING TO GIVE FLAME INTENSITY

Pre-heating of air and/or gas is necessary with certain fuels, for example producer gas and blast furnace gas, for attaining the temperatures required in reheating furnace practice. Thus, in one instance of the use of cold coke producer gas of a calorific value of 130 B.t.u./cu.ft. a furnace temperature of 1,140° C. was obtained with an air pre-heat of approximately 300 deg. C. at the recuperator, but since it was necessary that a furnace temperature of 1,200° C. should be reached this gas could not be used. It would have been necessary to use a burner with a higher degree of turbulence in the flame and an air pre-heat of 420 deg. C. to attain the additional intensity required. Accordingly in reheating furnaces, either regenerators or recuperators are used for pre-heating air, and gas, or both, where fuels of low calorific value are used.

FURNACE LOADING

The importance of the firing appliances and the structural features which determine the distribution of temperature have already been discussed. A third factor governing the fuel efficiency of a reheating furnace is the disposition of the charge in the furnace. This involves attention to the methods of handling, charging, discharging and, if required, transporting. The type of equipment depends upon whether the furnace is of the batch or continuous type.

BATCH FURNACES

Due attention to the design of equipment which may be readily and rapidly operated is reflected in the time saved in opening doors, and in proper placing of the charge on the hearth from the standpoint of quick and uniform heating. The hourly input of heat required by batch furnaces is largely governed by

the character of the furnace chamber; variations in the weight of material heated only affect the hourly rate to a limited degree. The point has been illustrated in Chapter 19, Table 11. The appliances which are used for handling are therefore of considerable importance. Lifting forks and peels, slung from runways or attached to a wheeled carriage, are used and should be capable of convenient and speedy operation. Porter bars are used for heavier articles, such as ingots and blooms. Charging machines of every degree of fashion from simple carriage types to power-operated and highly mechanical appliances are also called into service. The heaviest charges are heated on bogie carriages, or car bottoms, which are provided with sand seals. Alternatively, the furnace roof may be moved and the charge handled by overhead cranes.

In car type furnaces, particular attention should be devoted to hearth insulation and air leakages at sand seals, and particularly at the sides below the door. Cold bottoms can be due to air leakage at these points. The condition of bearings, adequate anchorage and robustness of rails or other type of bogie track are of particular importance in reheating furnace practice where temperatures are likely to be high. The problem of gas leakage between bogies is best overcome by means of furnace draught control and maintenance of zero pressure at car top level.

The batch furnace is favoured for forge, press and drop stamping work. The furnace dimensions, method of heating and general mode of operation are determined by the size and character of the material heated. For small blooms

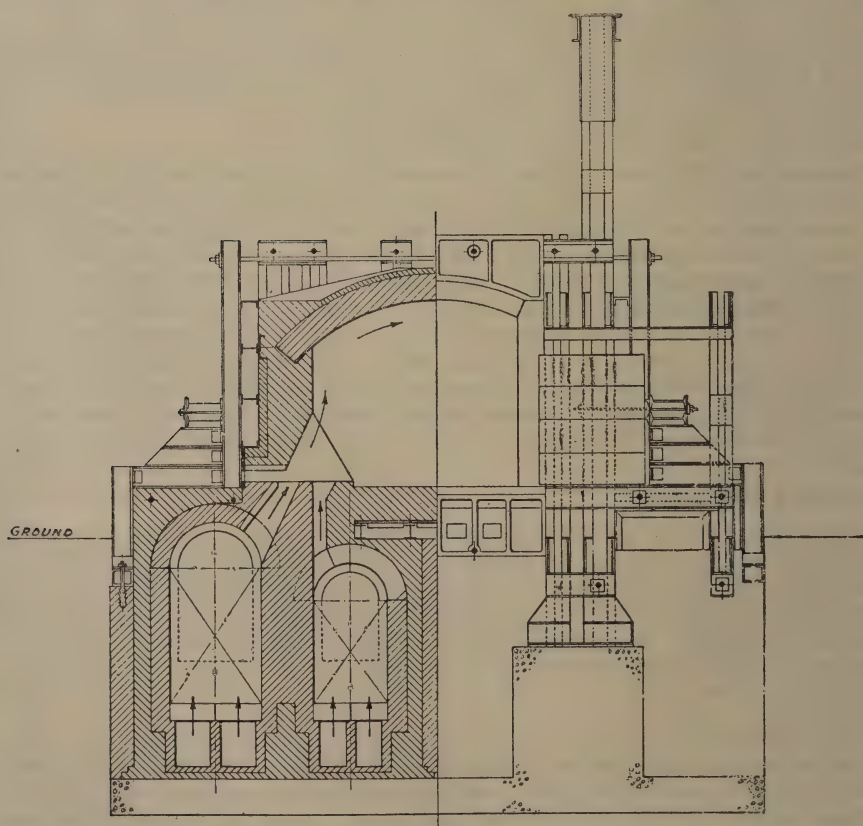


FIG. 15. Regenerative reversing producer gas furnace. Transverse section.

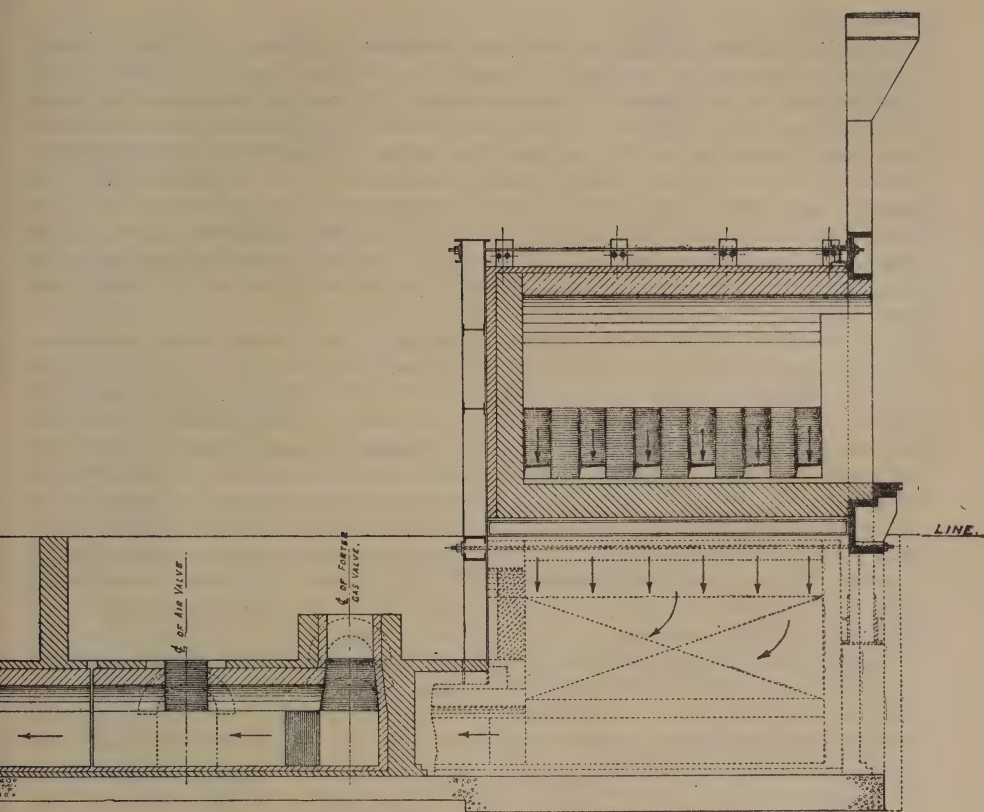


FIG. 16. Regenerative reversing producer gas furnace. Longitudinal section.

and billets rapid heating may be required in order to reduce scaling and, when heating steel, decarburisation of the surface.

A critical factor in the operation of such furnaces is the rate of heat input to the furnace. The most rapid heating is the most economical from the standpoint of fuel consumption, but materials may require slow heating for metallurgical reasons. It is a problem distinct from that of the continuous furnace, and cognisance must be taken of the heat absorbed by the furnace structure. The main controllable factors in operation are the rate of firing, the air supply and the balancing of the draught. In coal-fired furnaces much depends upon the skill of the fireman as to whether the fire is kept clean and even, and of the most suitable thickness, whether fuel of the correct size is fired, and the dampers and air slides correctly operated.

A regenerative reversing solid bottom type, fired by producer gas, is shown in Figs. 15, 16. The air regenerators are placed outside the gas regenerators and the ports are located in recessed combustion chambers at hearth level. The disposition of the gas and air reversing valves are shown in the longitudinal section of the furnace. Such a furnace is used for heating large forgings.

CONTINUOUS FURNACES

A great variety of design is used for continuous furnaces for reheating, an effective and popular design being the pusher type. Considerable investigation has been made into the fuel efficiency of this class of furnace, and a voluminous

literature may be consulted.

The continuous furnace is favoured because it offers a relatively simple method of conveying, and at the same time heating, material, and hearths may be constructed capable of withstanding high temperatures and the action of the scale falling from the charge. The chamber is built with either side or end discharge according to the conditions which obtain for the transfer of the heated material to the forming plant. Furnaces of the side-discharge type must be used when long bars of comparatively small section have to be heated for rolling in continuous mills. In order to avoid excessive speeds at the finishing pass, such bars must enter the first stands of the mill slowly. Accordingly, the rear end of the bar must be kept in the furnace as the leading end enters the first pass.

An essential technical requirement is that the furnace must be able to provide the necessary uniform final temperature throughout the ingot, bloom or slab. Where a solid hearth is used there is an inevitable chill due to the absorption of heat by the material of the hearth, or by the skid bars over which the charge is pushed. Provision with heavier sections may accordingly be made towards the discharging or soaking end to turn over the material by convenient means, so that the cold side may be exposed to the hot radiating surfaces of the furnace chamber. Ingots or blooms up to 8 inches diameter may be allowed to drop over the edge of the skids on to a refractory forehearth. Heavier blooms can be operated in this way if the forehearth is reinforced with heavy metal masses, and the temperature not too high to give adequate durability of the hearth.

Ingot manipulation may be used for heavy masses up to 23 inches diameter. The forehearth may be constructed of basic refractory materials, comprising magnesite, chrome or spinel bricks, stabilized dolomite or other suitable material, as brickwork or monolith. These do not form slag with scale from

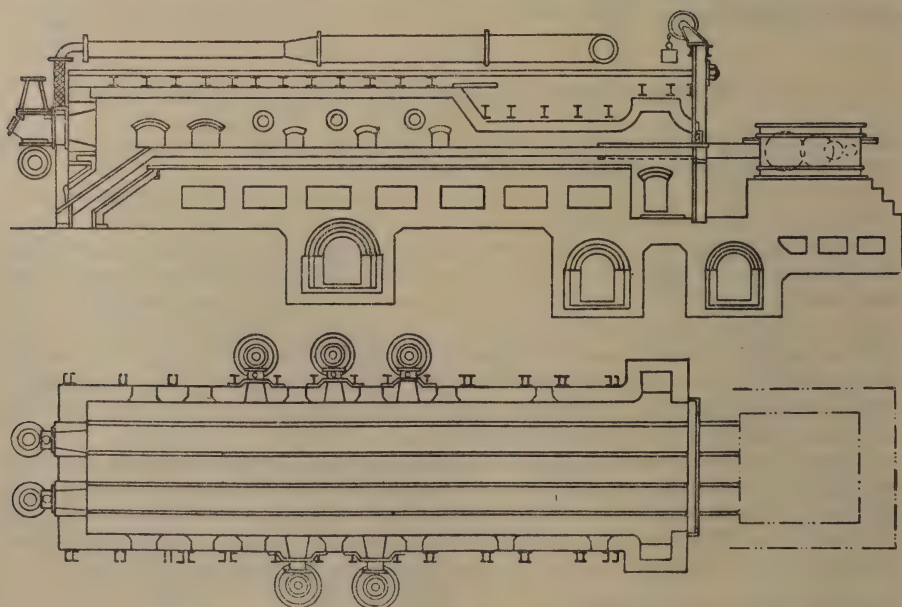


FIG. 17. Continuous pusher gas-fired reheating furnace.

the charge. The hearth remains dry, and can be kept clean readily by raking out the scale.

The charge is moved by power-driven mechanism, electrical, hydraulic or other available means. Particular care has to be taken to avoid the separate pieces riding over one another or fouling the side walls of the furnace. Accordingly, doors placed at suitable intervals may be provided to give accessibility. A continuous pusher type of furnace is shown in Fig. 17. It is equipped with end and side burners for gaseous fuel, and end discharge from a horizontal hearth.

In order to assist the attainment of uniformity and to raise the output of the furnace, the skid bars may be raised either for the whole or a section of the furnace chamber to permit of underfiring. The problem of supporting, anchoring and so safeguarding the rigidity of the bars introduces maintenance difficulties of no mean order, so that in many mills separate batch soaking furnaces are frequently employed in order to ensure the required standard of heating.

TIMES OF HEATING

In the heating of steel, a formula has been given by Helweg for deriving the final character of the soaking at the discharge end of the furnace.

If t = heating time in the furnace, minutes.

ΔL = corresponding length of the hearth, metres.

V = velocity of the charge over the hearth, metres per hour.

D = diffusivity of the charge, square metres per hour.

l = vertical thickness of the material of the charge,

a specific minimum value for the heating time, or alternatively for the corresponding length of hearth required is given by the equations:

$$t \geq \frac{18l^2}{D} \quad \Delta L \geq 0.3 \frac{l^2}{D} V$$

The degree of soaking, defined as the temperature gradient within the mass of the charge, $\Delta \theta$ is related to the rate of temperature increase on the surface of the charge, $\Delta \theta'$ by the equation,

$$\Delta \theta = \frac{l^2}{2D} \cdot \Delta \theta'$$

Where the surface is observed by the use of an optical pyrometer, scale should first be removed from the surface of the heated metal. In practice, times of heating vary widely according to the class of material heated, the process and the degree of uniformity of heating required. Further, the standard of heating may be judged, not from the temperature observations, but from the behaviour of the material, when worked, e.g. the power taken by the mills in rolling, or the accuracy of movement of the tool in piercing.

An analysis of existing data on the times of reheating metals in continuous furnaces has been made by Sarjant¹⁴.

APPLICATION OF HEAT RECOVERY

The application of heat recovery to reheating furnaces is practised with advantage. In batch furnaces the exhaust gas must leave the furnace at a high temperature, and accordingly an appreciable economy may be achieved by utilising the sensible heat of the exhaust gases for preheating air or fuel gas or both. In general it is possible to utilize at least half of the heat contained in the exhaust gas as air preheat.

Firebrick or metallic recuperators and regenerators may be used.

(i) *Recuperators*. Firebrick recuperators may leak, since firebricks, and particularly the cements used, tend to shrink with continued heating. Further, any refractory structure is subjected on heating and cooling to expansion and contraction, and the repetition of these movements ultimately produces dis-

turbance of the refractory at the joints, which become a serious source of air leakage. Such difficulties are likely to be aggravated by ground vibration such as arises from the use of heavy mechanically-operated hammers or presses. On the other hand, with suitable ground conditions and adequate means of accessibility and maintenance, firebrick recuperators have their uses.

Metallic recuperators are becoming more widely used, since metals have been developed which are suitable for the purpose. They have a low heat capacity, and the construction is readily made air-tight. Accordingly high air velocities may be carried, and the degree of utilisation of the available heating surface is increased, since the coefficients of heat transfer are higher. These are increased by the better heat conductivity of the material of the tube walls as well as by the increased velocities. The limiting condition governing the abstraction of heat from the waste gases is determined by the pressure drop permissible. With induced draught any desired velocities may be obtained, but where this provision is impracticable the use of refractory surfaces in conjunction with the metallic surfaces effecting the heat exchange is an advantage. The coefficient of heat transfer by convection in slowly-moving gases is relatively low, and this may be compensated for by the radiation from the hot refractory surfaces (Chapter 9).

The upper limit of attainable pre-heat of the air in metallic recuperators is 850°C. , being fixed by the durability of the material of the recuperator tubes. Above this temperature regenerators must be used. In furnaces fired with gas or pulverized fuel there does not appear to be an upper limit for the usable hot air temperature as far as the durability of the furnace is concerned, because by reducing the amount of fuel burnt per hour, and with a suitable distribution of burners, any desired low working temperature can be maintained. On the other hand, in grate firing the temperature of the primary air is kept down to about 300°C. , since burning of the grate and clinkering troubles may develop above this limit. Furthermore, in order to obtain smokeless operation, it is inevitable that hand firing of solid fuel will be progressively replaced by mechanical stoking.

(ii) *Regenerators.* Reversing regenerators are most effective in applications in which the temperatures of the exhaust gases are not subjected to large cycles of variation. They have a large capacity for heat storage, and require much ground space for the regenerator chambers, accompanying flues, and reversing valves. Where applicable they are the most efficient form of heat exchanger, and require the least attention for maintenance and renewals.

Where regenerators are used burners must be of simple design, since gas and air pressures are relatively low, and the burner throat becomes on reversal the outlet flue.

(iii) *Pre-heating Chambers.* The continuous furnace is a combination of heating chamber and pre-heater, since at the charging end the sensible heat of the products of combustion serves to pre-heat the incoming charge. In batch furnaces it is occasionally the practice to lead the waste products of combustion from one chamber to pre-heat the charge in another, but a difficulty may be encountered in overcoming the loss of draught resulting from the resistances due to connecting flues, and the frequent opening of charging doors.

(iv) *Waste Heat Boilers.* The waste heat boiler is another means of recovering sensible heat in the products of combustion leaving the working chamber of a batch furnace. Its advantage depends largely on the economics of each individual case, whether the value of the steam raised is adequate compensation for the costs of installation and operation of the boiler. Cyclical variations of temperature of the waste gases, the avoidance of excessive inleakage of cold air, and whether the resulting variations of output of steam may be economically

dealt with have to be considered. It has been in many older installations the practice to apply auxiliary firing to the boiler to maintain the steam output when the furnace output of waste heat falls off, but this practice does not always provide the most economical combustion. The subject is discussed in Chapter 21.

FACTORS DETERMINING THE PERFORMANCE OF REHEATING FURNACES

By far the most important factor controlling the fuel efficiency of a reheating furnace is that of load in relation to the dimensions of the furnace chamber. The quality of heat absorbed by the structure in bringing the furnace to a required condition is mainly determined by the design and structural features of the furnace, but the rate at which heat may be developed in the chamber and the manner at which the heat absorbing surfaces of the charge are exposed to the heat are controllable.

For similar types of furnaces a relationship exists between the ratio of the useful heat absorbed by the charge to the total heat input, usually defined as the "thermal efficiency" and the rate at which the useful heat is absorbed in the charge per unit of "heating surface". By "heating surface" is here meant the total heat-absorbing surface. When the hearth is covered with stock, then strictly the total heat absorbing surface should include the crown, side walls, hearth and the surface area of the stock exposed to radiation less the area of hearth covered. In practice the "heating surface" constitutes the flame-swept surfaces, and is roughly approximate in many reheating furnaces to the area of the refractory surfaces. In simple terms it amounts to relating the fuel used per ton to the rate of throughput on a comparative basis of furnace size.

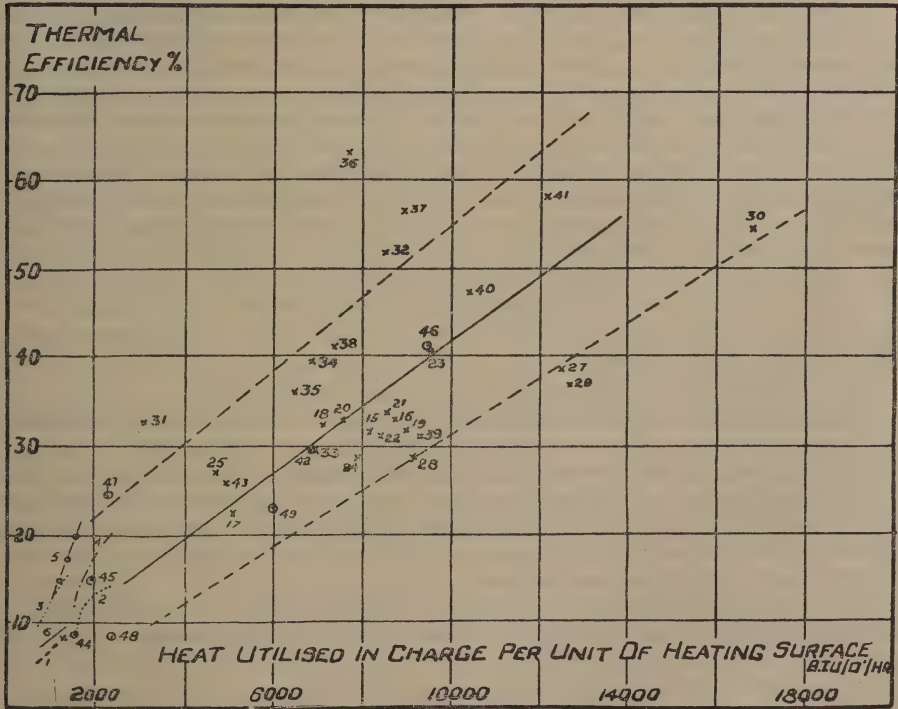


Fig. 18. Relation between thermal efficiency and rate of utilization of heating surface for furnaces of related type.

Figures in the diagram relate to different furnaces, as referred to in the text.

Using the above basis of comparison, the relationship has been shown in Fig. 18. Most of the examples illustrated, the full record of which may be obtained from the paper¹⁴ quoted refer to continuous furnaces.

More recently the same relationship has been shown to apply to soaking pits.

The curves for furnaces, shown in 1 to 6, Fig. 18, are derived from plant in which accurate knowledge of the fuel consumption and output was available. They refer to conditions of slow heating in which a high standard of uniformity of temperature was required.

Furnaces 15–23 were of the continuous pusher type fired by coke oven gas and heating long billets covering 50–75 per cent. of the hearth area.

Nos. 24, 25 refer to furnaces of the same size and similar class of charge and output. No. 24 was fired by producer gas, No. 25 by mixed gas of calorific value 210 B.Th.U. per cubic foot.

Nos. 26–30 show in a marked manner the general relationship between thermal efficiency and rate of utilisation of heat per unit of heating surface in spite of some variations in the proportion of waste heat appearing in the products of combustion.

Groups 31, 32 and 33–35 are comparable amongst themselves.

Nos. 36–41 refer to a series of tests by Chandler¹⁵ in which the performance of continuous pusher furnaces equipped with recuperators contrasted with that of non-continuous regenerative reversing furnaces. Nos. 42–49 are all furnaces of varied type, showing the general relationship. The improvement of No. 45 over No. 44 was ascribed to the application of air recuperation in alloy steel tubes and insulation of the furnace.

Other points emerging from such comparisons are that thermal efficiencies of the order of 40 per cent. have been obtained from non-continuous regenerative furnaces, but that at the same time structure losses resulting from keeping the whole of the chamber at the working temperature accounted for approximately 35 per cent. of the heat of the fuel. Pusher-type continuous furnaces have on the other hand been constructed to give efficiencies well over 40 per cent., and even 70 per cent., approaching the thermal economy of an efficient boiler plant. Such high efficiencies are experienced only where a rapid throughput is practicable as with small bars or billets 2–4 inches in section. The furnaces are generally large with tonnages of the order of 30–60 tons per hour, and the throughput reckoned on the hearth surface rising to nearly 100 lb. per square foot per hour. With ingots and heavier blooms the practicable rates of output fall with increase of section to rates of the order of 30 lb. per square foot of hearth area per hour.

The improvements made in reheating furnace practice are :

(i) Underfiring as well as overfiring in continuous furnaces. In the most efficient types the chamber is divided into three sections; a forehearth, in which the charge is pushed over skids on a solid hearth; a main heating hearth in which heating is applied from above and below, and the charge is carried on water-cooled skids; and a soaking hearth with a low crown to enable a positive pressure to be carried in the chamber with the object of preventing air in-leakage from the end discharge doors.

(ii) A high standard of gas/air control, and avoidance of excess air, for which automatic damper control is applied to assist this latter requirement.

(iii) Insulation and gas-tightness in the furnace structure.

(iv) Adequate provision of instruments, particularly as regards measurement of temperature conditions, rate of fuel supply, and sensitive indication of furnace draught.

The reheating furnace has its counterpart in all types of continuous annealing

furnaces, lehrs, continuous and intermittent ovens and kilns, and many other types of furnace used in the arts. Accordingly many of the recommendations contained in the discussion of these varied types in various parts of this book may be equally applicable to other industries.

SOAKING PITS

The combination of the large open hearth furnace and the continuous rolling mill involves the provision of means whereby hot ingots may be fed to the mill without being allowed to go cold. The plant used is known as a soaking pit. It is virtually a vertical reheating furnace into which hot ingots are fed to be heated for rolling, and the construction in the earlier forms was a series of cells sunk in the ground to take in one or more ingots. Later the cells were put into communication with one another along the lower section for the passage of heating gases, leaving arches to support the 'lean' of the ingots. More recently the pits have been increased in size, each to hold 60–120 tons of ingots, and constructed in batteries. They are fired by producer gas, coke oven gas, blast furnace gas, a mixture of coke oven gas and blast furnace gas, or oil, and employing recuperators, regenerators or waste heat recovery for the raising of steam. These pits have either arched or suspended movable covers operated in one or more sections. Systematic removal of slag and scale is necessary in order to limit the build-up of the bottoms.

In certain cases a layer of coke breeze is used to absorb the slag, spent breeze and slag being removed at regular intervals.

The heat requirement may vary from 2.5 to 15 therms per ton of material heated according to temperature and class of charge, plant and conditions of operation. Scaling losses are of the order of $1\frac{1}{2}$ –3 per cent. Outputs based on the area of hearth may be as high as 150 lb./sq.ft./hr. In modern practice, in the heating of ordinary and special steels, it has been recognised that accurate control of temperature and atmosphere of the pit is essential and fully automatic control of these as well as of pit pressure is almost always included. Gas and air meters and pit pressure recorders are other useful instruments.

A cross-section through a modern soaking pit installation is shown in Fig. 19.

Continuous furnaces of the bogie type may be used for pre-heating the ingots prior to charging into the pits, and in some instances such furnaces are used instead of soaking pits for final heating of the ingots.

HEAT TREATMENT FURNACES

Heat treatment operations are carried out in order to produce some desired physical condition in the material heated. The treatment usually requires the application of a specific cycle of temperature change in a given time. It may be followed by an operation external to the furnace, which imposes the incorporation in the design of special mechanical appliances for transferring the charge to the plant in which the external treatment is applied. For example, stock may have to be conveyed through a hardening furnace and then quenched, say in oil, or it may be necessary to apply a specific type of cooling treatment.

Practically all the general principles so far discussed apply in some degree to heat treatment furnaces, but the latter have certain special features as a class, which amount in effect to the need for a high standard of temperature control and uniformity.

CHARACTERISTICS OF HEAT TREATMENT FURNACES

Since heat treatment operations generally follow a number of other manufacturing operations, as a result of which the article treated is much enhanced

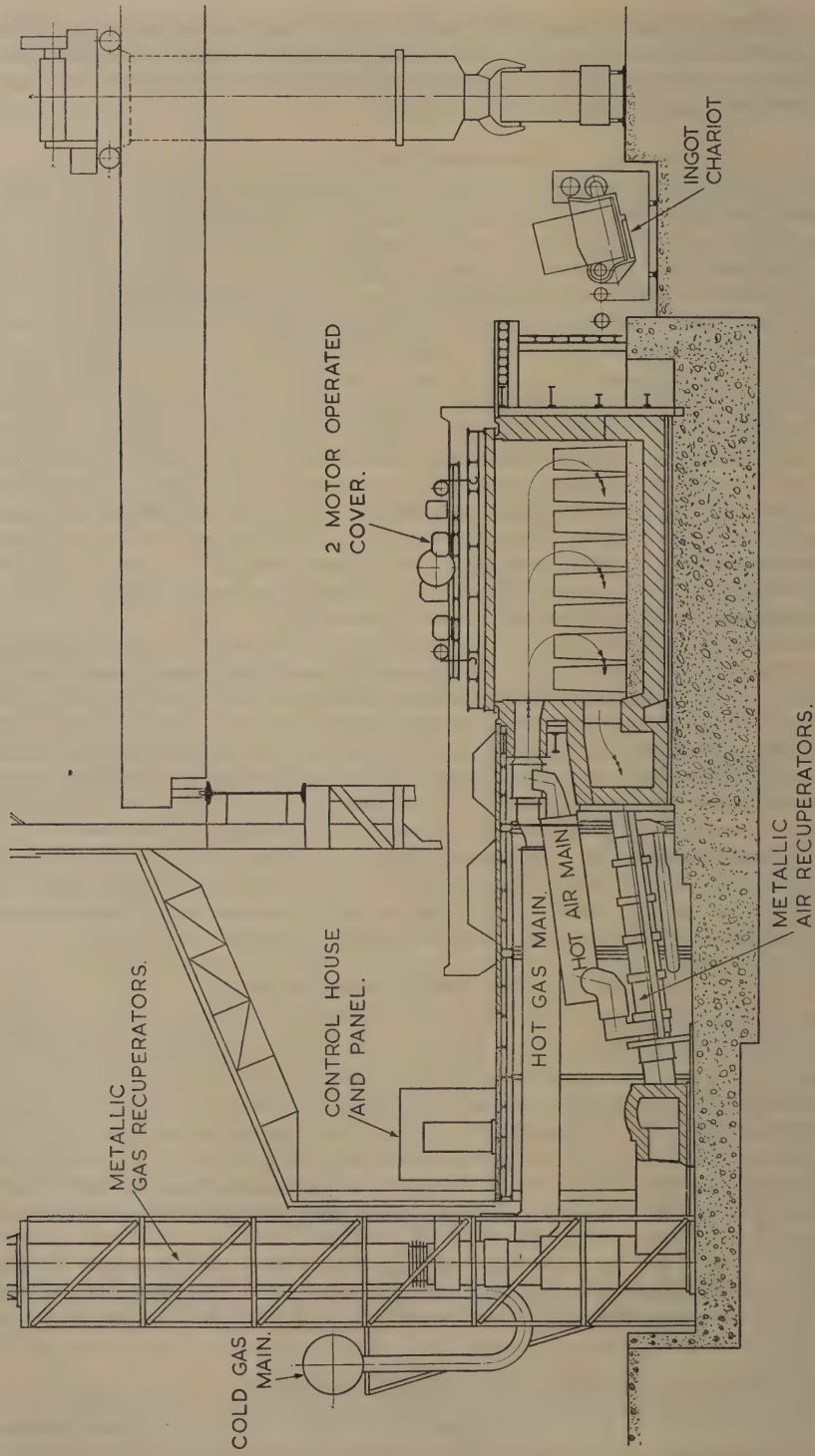


FIG. 19. One-way fired soaking pit.

in value, greater control must be exercised to avoid loss due to spoilage than in earlier operations. Machining may have been completed, so the condition of the surface may require consideration. Warpage may be of significance. Most important of all, there may be quite a narrow tolerance in the limits of the permissible range of temperature of treatment in order to obtain the desired physical properties in the material heated. Not only must the material be heated more uniformly, but the temperature to which it is heated must be more accurately controlled than in other furnaces. This implies a greater degree of refinement in the firing, and the need for a greater use of control instruments. Accordingly it becomes advantageous to use fuels and furnaces capable of the requisite standard of scientific control.

Pyrometric control is essential in most heat treatment furnaces. Recording instruments, of the multiple reading type, provide the most effective means of controlling the performance of a battery of these furnaces. Frequent calibration of both couple and instrument are necessary.

In all types of heat treatment furnaces, both large and small, electricity is applicable.

Further, temperatures are relatively low, in comparison with the types of plant already discussed. Accordingly a greater degree of mechanization becomes practicable, and in this respect a remarkable range of conveying and other types of auxiliary appliance has been called into service, constructed of suitable heat-resisting materials.

GENERAL UTILITY FURNACES

There are many types of straightforward heating operations—annealing, hardening, tempering, carburizing—requiring the use of temperatures below $1,000^{\circ}\text{C.}$, these operations being performed in a simple type of batch furnace. The furnace then becomes in effect a general purpose furnace, and the sole problem of the designer is to apply the necessary flexibility of heating, uniformity of temperature within the limits required, and thermal economy. Floor space available may determine the selection of fuel.

In such furnaces the following features of design and operation are important in the control of efficiency :

(i) Location of burners and flue offtakes to give quick and accurate attainment of uniformity of temperature. In small furnaces bottom heat should be provided, either by the location of heating flues in the hearth or by arranging for the waste gas flues to traverse the brickwork of the hearth.

(ii) Recuperation of waste heat and pre-heating of the air for combustion by the incorporation of the recuperator elements in the main structure of the furnace.

(iii) Use of refractories of low thermal capacity, since general purpose furnaces are normally used intermittently and the amount of fuel used for lighting-up becomes an item of importance. Hearths have to withstand wear and attrition, and the working surface must be made of a hard firebrick.

(iv) High grade external insulation.

(v) Robust framework, well-fitting, well-lagged doors, readily-controlled dampers and freedom from leakage.

(vi) Pressure gauges or simple orifice flow meters on the fuel, if oil or gas.

In small general purpose furnaces, cold air may enter round doors, through pyrometer holes, lighting-up ports and sight holes. This inleakage is increased unnecessarily when the chimney provides excessive draught. For venting the waste products outside the shop, cowls should be provided into which the necessary length of shortened chimney is allowed to discharge the furnace gases.

In the larger types of general utility furnaces the choice of fuel may be

extended to include fuels other than those most readily controlled. Raw producer gas, pulverized fuel, coal fired by underfeed stoker, coke and oil may be applied efficiently. Many are operated on coal, hand-fired, but the trend in practice is towards the replacement of hand firing by more controllable forms of heating.

SINGLE PURPOSE FURNACES

It would require a separate treatise to describe adequately the many forms of heat treatment furnaces devoted to specific operations, and to enumerate the special points to be watched in maintaining their efficiency. They are usually constructed by expert furnace builders, who have developed their special features as the result of long experience. It is a good practice to enlist the assistance of the constructor at the outset in drawing up simple explanations of the method of operation, with clear sketches, to assist the operative staff to make the best use of the furnace. The essential points to be watched in maintenance as well as in operation should be indicated.

The following survey is restricted to a discussion of selected types, with the object of giving an introduction to a complex problem.

In the construction of single purpose furnaces for heat treatment in addition to the major principles which have already been discussed both in Chapter 19 and in parts of this chapter, a number of special points have to be given consideration. These are: space uniformity of temperature, temperature regulation with regard to time, protection of material, handling of material.

Space Uniformity of Temperature.

Ideally, to obtain rapid and uniform heating a metal should be exposed to a heating medium which imparts its heat to the charge equally on all sides. The lead bath and the salt bath meet this requirement, but they cannot be applied universally. An electric furnace with resistors in crown and hearth as well as side walls is the next most suitable agent for the purpose. In all heating a temperature difference must be set up between the heating medium and the surface of the charge. This difference is large in the early stages of heating and diminishes as the soaking stage is reached.

In batch furnaces the temperature differences must be controlled by the firing rate solely; in continuous furnaces by the control of throughput as well as that of rate of firing. Low rates of heating are in general conducive to a high degree of uniformity, but the thermal efficiency of the operation may thereby be impaired. The space uniformity at any one moment depends mainly on the design of the furnace and the disposition of the charge.

Various expedients are used to assist in securing the object in view. The most satisfactory expedient lies in the disposition of the burners or ports through which the heating gases enter the working chamber. Others are:

- (a) the use of muffles or perforated walls.
- (b) the use of "lazy" flame or, in electric furnaces, of controlled temperature resistors.
- (c) forced circulation of hot gases.
- (d) disposition of the heating surfaces at a distance from the charge.

(a) Muffles retard heat transfer and accordingly assist temperature equalisation in the charge. They also permit of the use of controlled atmospheres and therefore serve for the protection of the material heated. An inverse of the ordinary muffle method is to allow the heat to be developed in a muffle with the flame inside. It is developed to its most advanced degree by the use of heat-resisting metal tubes inside of which gas is burnt. The tubes are suitably disposed in the furnace chamber to heat the charge by radiation. These are used in the so-called radiant tube furnaces.

In fireclay muffles the limiting capacity in rate of heating is of the order of 5,000 B.t.u./sq. ft./hr. for muffles of not more than 1 foot in the smallest dimension, and 3,000 B.Th.U. up to 3 feet.

Greater thermal efficiency is obtained where it is practicable to admit the products of combustion to the interior of the muffle. This is generally referred to as *semi-muffle heating*.

Avoidance of cracking in monolithic muffles and care of muffle brickwork in built-up muffles are essential elements of efficient practice.

Carborundum is used to increase conduction of heat. Heat-resisting metals are also applied to muffle practice.

In principle, the use of perforated walls is similar to method (i) (d), because the charge is exposed to radiation from small bright spots located at a distance from the charge. Perforated walls are not an invariably successful expedient in attaining uniformity of temperature, for where the gases are moving slowly the hot gases tend to be discharged at the highest ports and they may serve to promote circulation of gases in such a manner that cold layers of gas may collect more readily at the hearth level. Further, they are not necessarily of good stability, and being thin and adjacent to the combustion chamber are subject to failure.

(b) *The "Lazy" Flame*. The use of the "diffusion" burner has already been mentioned. In this appliance the fuel gas and air are discharged at separate and adjacent ports, and are allowed slowly to diffuse into one another giving a long flame. The use of producer gas, discharged at ports lying adjacent to relatively large air ports in such a manner that both port velocities are low, gives a soft lazy flame which is particularly effective in giving space uniformity of temperature.

Low temperature electric lamps or gas-heated surfaces emitting a high proportion of infra-red radiation and disposed in large numbers to give uniform heating have been applied to the drying of enamelled ware.

(c) *Forced Circulation*. For low temperature heating below 750° C. there is no form of heating so effective in attaining uniformity of temperature as forced circulation of the products of combustion. Reference to Chapter 9 will indicate the influence of velocity on the coefficients of heat transfer at low temperatures. Further, cognisance must be taken of the gas radiation from the products of combustion, from which it must be apparent that by circulation of the gases at velocities which will overcome those of the natural convection currents, improvement in the uniformity of heating must follow. A minimum desirable velocity is of the order of 20 feet per second, but higher velocities of the order of 60 feet per second and upwards are still more desirable. The optimum value must depend upon standards of uniformity required and the gas-tightness of the furnace structure.

With this type of furnace the heating is generally indirect, combustion taking place in a separate chamber. (See Figs. 20–22.) Alternatively, burners may be placed in side walls in separate combustion chambers and the products drawn by induction into the main circulating stream. The hot gases are continually recirculated through the furnace by means of a fan, in any desired direction. A reversing valve may be provided to give alternative direction of flow. A temperature difference of only 2 deg. C. at 600° C. between top and bottom of a vertical furnace 30 feet high in the chamber is attainable by such means. The recirculation fan is placed in a lagged housing, and the bearings are usually water-cooled. The fan is, of course, constructed of heat-resisting metal. Temperature control is readily effected on the main fuel valve, and automatic temperature control thereby made relatively simple.

(d) *Disposition of Heating Surfaces*. This implies attention to the disposition

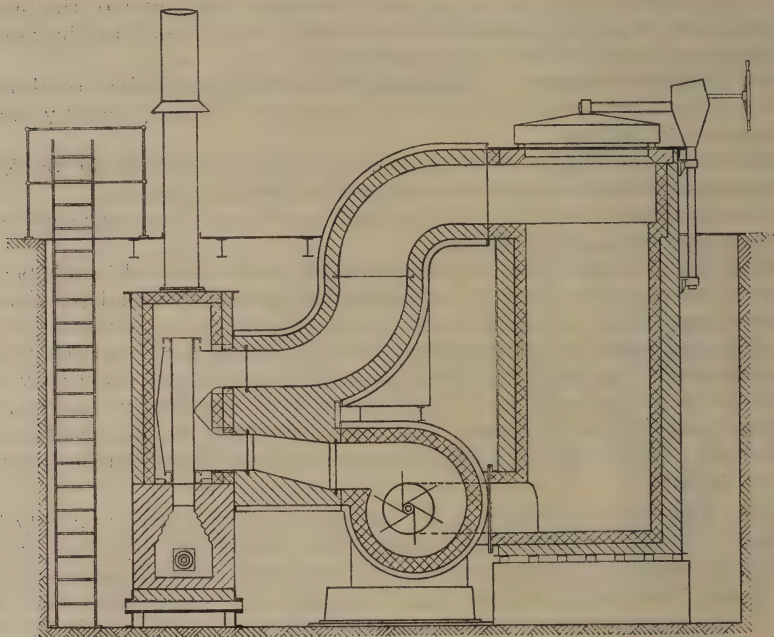


FIG. 20. Pit-type furnace (with forced circulation).

of the charge in the furnace as well as to the location of the hot spots. The further the hot spot is from the material heated the more is the heat diffused. Raising the crown, placing the side walls some distance back from the working hearth, the provision of well-radiused crowns, the use of recessed bricks in internal wall surfaces, underfiring of hearths, and raising the charge on supports are all expedients serving the same purpose.

Finally, in attaining uniformity of temperature there is nothing so important as keeping cold air from leaking in.

Temperature Regulation

A pyrometer must be used. The indicating or recording instrument should be placed at a safe point close to the controls. It should be easy to read, and, if of the recording type, give a distinct record, readily observable by the furnace operator. It should be robust, dust-proof, accessible, simple to maintain, and installed in such a manner that its importance in the furnace operation is readily appreciated. It is becoming the practice in the most efficient installations to incorporate all control instruments in a panel, placed either in a protected cabin or in such a position that a maximum effectiveness is attained. A clock is also necessary.

Automatic temperature control is the logical development of efficient furnace technique.

Protection of the Charge

This subject has already been discussed under "Control of Furnace Atmosphere," Chapter 9. For general heat treatment of metals it becomes a problem in combustion control. For special processes such as bright annealing some form of muffle heating or its equivalent is used and a special atmosphere supplied from an external gas generator, with the possible addition of automatic pressure regulation.

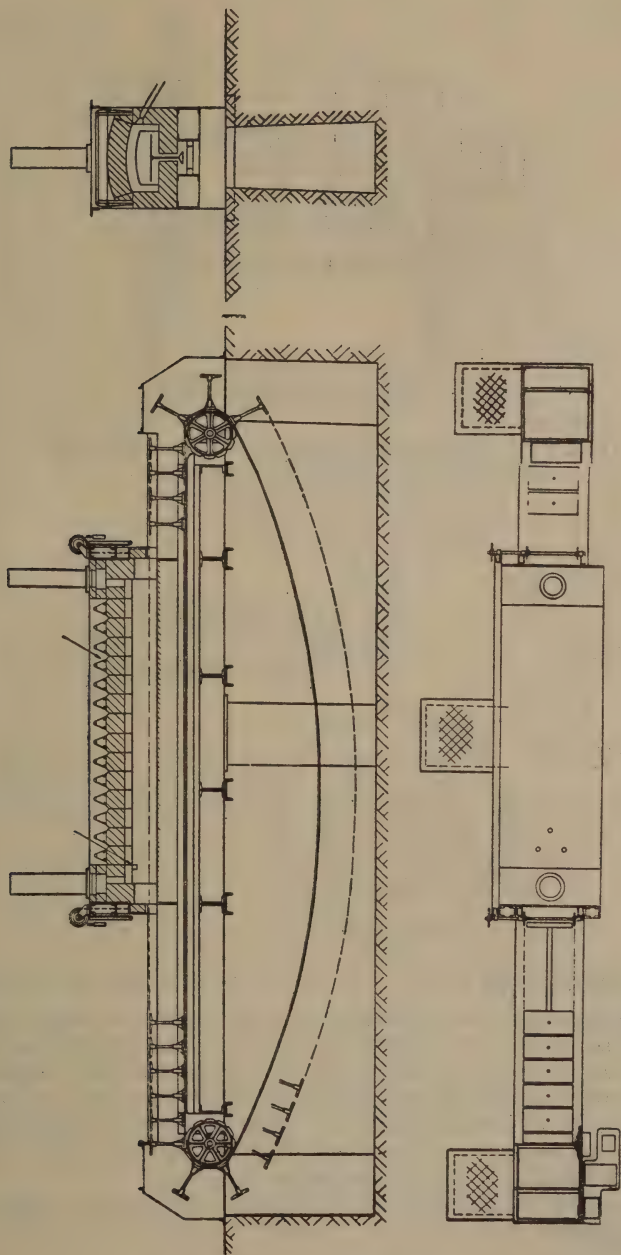


FIG. 21. Conveyor type Furnace.

Handling of the Charge: Mechanization

In recent years there have been important developments in the mechanization of reheating furnaces. These have not been limited to larger furnaces (e.g. of 3-ton ingot capacity) but are applicable to small heat treatment furnaces also. The greater range and availability of heat-resistant alloys has

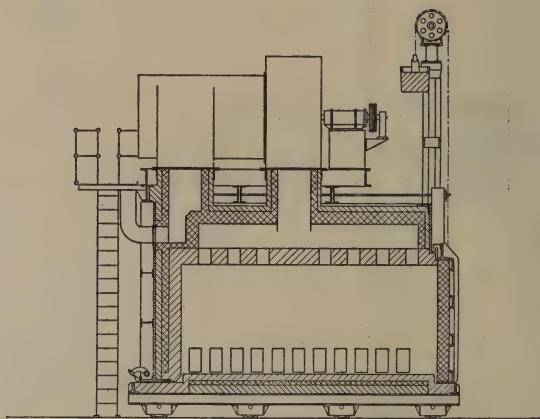


FIG. 22. Large Bogie type Furnace, for stress relieving, annealing etc. (using forced circulation).

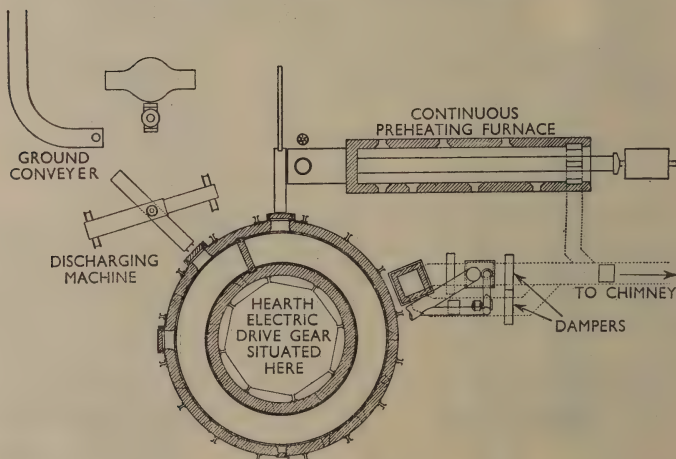


FIG. 23. Rotary Hearth furnace, fired by coke producer gas, with recuperator.

facilitated the extended use of moving hearths, in both annular rotating furnaces and those of the continuous bogie type. The latter provide a means of heating relatively large charges for both re-heating and heat treatment.

In many heat treatment operations the handling of the charge is mechanized to save labour, for convenience and for rapid discharge to quenching tanks. As with reheating furnaces pusher mechanism is frequently used. Where small parts are to be treated they may be pushed in trays.

Examples of the furnaces referred to in the sections below dealing with this subject are shown in Figs. 21-29.

Conveyor Furnaces

Chain conveyors are convenient for automatic furnaces. The design of the chain varies widely with the shape of the material to be transported. Below 650°C . commercial link chains are frequently used, particularly when the chain does not pass through the heating chamber, but carries an attachment reaching into the furnace. For operation above 650°C . more specialized designs may be necessary.

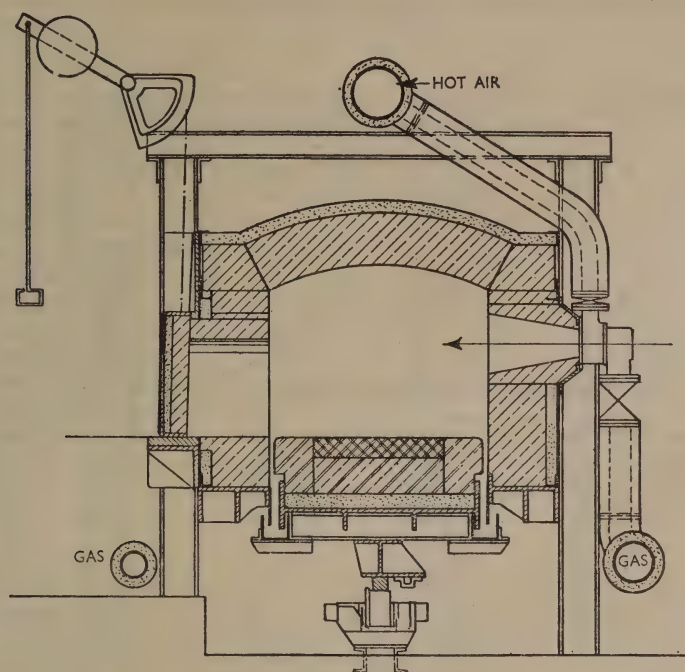


FIG. 24. Rotary Furnace, cross section.

The take-up of the chain due to expansion when it becomes heated must be carefully watched and the tension on the spring controlling the take-up adjusted to avoid stresses which may cause the chain to be strained. Sprocket teeth on driving wheels must be given adequate clearance in order to avoid the links riding up on the side of the tooth.

Chains passing through the working chamber are subjected to repeated heating and cooling even if the return passes through a closed chamber below the hearth, and this cyclical change of temperature imposes a repeated stress which can lead to cracking and failure, particularly in incompletely stable materials. The incidence of cracking is promoted by passage of the hot chain through a quenching bath, and under such conditions careful selection of the materials of the chain is imperative. Certain austenitic alloys are the most suitable, since they exhibit an absence of change points on heating and cooling, and remain stable under the conditions of service.

Success with chain conveyors depends not only on the properties of the chain, but also on uniform distribution of temperature in the furnace. If parallel strands of the chain are subjected to great differences of temperature unequal expansion is bound to arise. Wherever in any individual members uneven distribution of temperature occurs the resultant stresses cause warpage. Overheating can result in failure due to creep and oxidation. Chains may be equipped with refractory tops and may then transport material through very hot furnaces.

An important element of conveyor design is the proportion of sensible heat lost in the conveyor, and this may be of serious consequence in electrical heating.

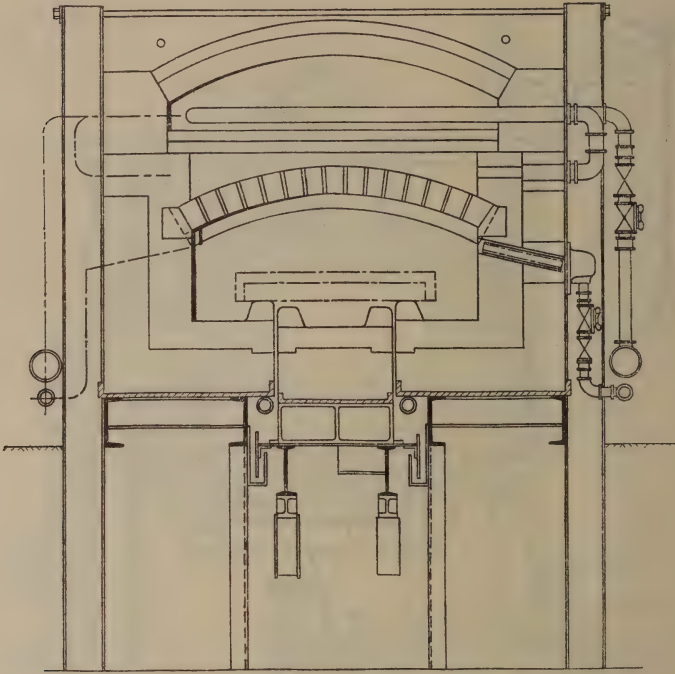


FIG. 25. Walking Beam Furnace.

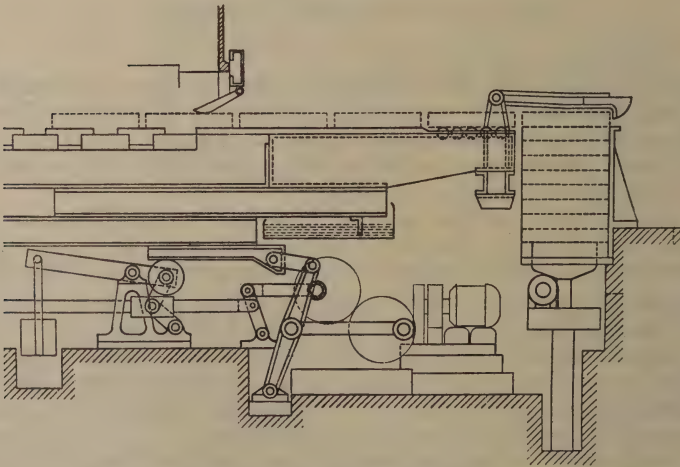


FIG. 26. Walking Beam Furnace. Elevation of conveying gear.

Roller Conveyors

Roller conveyors are usually made of heat-resisting metals though they may also be of composite construction in which refractories play a part. Where made of metal they must rotate just enough to prevent any noticeable temperature difference between top and bottom; otherwise warping is inevitable. For the conveyance of sheets and plates discs may be used on water-cooled cross-shafts, the discs being staggered on successive shafts. The water-cooling may give rise to considerable heat losses. The driving of the rollers is effected

by means of worm gear drives or level gears on a lay shaft, both being external to the furnace.

Monorail Conveyors

Monorail conveyors are favoured where only part of the piece is to be heated, as for instance in brazing work, and in japanning ovens.

Special Conveyors. The Walking Beam Furnace

There are now many types of special conveyors, notably the type known as the *walking beam*, used for conveying sheets in annealing and normalizing furnaces. In these the carrier beam is supported by means of rocker bars, which normally rest below the hearth. This member is moved by suitable mechanism to lift the material off its supports placed between the moving beams, carry it forward and deposit it a distance forward again on its supports. Means have been devised for heating the sheets from below as well as from above, and accordingly the design and technique of operation of such furnaces has become a specialized field.

Vertical conveyors are amongst the less common types. Rotating drum furnaces are used for small articles that can be readily handled in heaped masses, and will travel freely and pass through openings without choking them, such as screws, rivets, nuts, rings, punchings.

Moving Hearths

Moving hearths are operated in the form of bogies or car bottoms, as circular or as annular hearths. The last two are usually supported on rollers and are moved by a suitable type of drive and gearing. They have the important advantage that the hearth is always heated, which is conducive to rapid and uniform heating of the stock. The bogie type is favoured for heavy masses. It may be applied to the batch furnace, the tunnel continuous furnace, or to the compartment furnace. This last is in effect a tunnel furnace divided into sections by means of partition doors which are all raised together to allow the bogies or car bottoms to be moved forward to the next compartment. By this means any specified cycle of heating and cooling can be applied by varying the time of moving the bogies forward and controlling the temperature change in each chamber.

Top-hat Furnace

Finally, there is the type of sheet annealing furnace in which the sheets are piled on bogie carriages running on a ball track, and shielded from the flame by the use of a steel cover. The old type of furnace consisted of a brick chamber which had one or more fireplaces disposed at convenient points according to the ideas of the builder. These have been replaced by the continuous type, employing the tunnel or mechanical conveyor, and by a batch type operating on piled sheets over which the furnace body is dropped.

This last type, referred to colloquially as the "top-hat" furnace, is heated either electrically or by means of gaseous fuel. In the electrical type the resistors are placed inside the furnace cover which is lifted over the pile of sheets. In the gas-fired type, use is made of the radiant tube already described, and arranged either vertically or horizontally. Controlled atmospheres are operated underneath the covers by the admission of suitable gas from an external generator. The controlled atmosphere may be subjected to forced circulation in order to assist in attaining uniformity of temperature within the charge.

This type is suitable for moderate annealing temperatures. The operation of the furnace is comparatively simple as clean gas is used. Each radiant tube made of heat-resisting alloy is provided with a simple burner blowing into

the tube. The burners are connected to gas pipes and combustion may be controlled by any of the conventional methods.

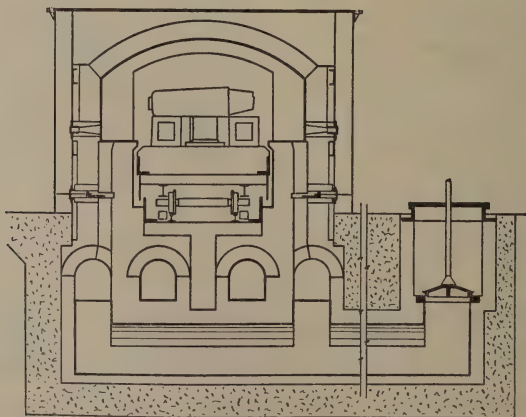
For large outputs of material, mechanical furnaces have many advantages. They are virtually complicated machines, and may be fully equipped with instruments such as combustion controls, pyrometers and draught regulators. Temperature and atmosphere control are matters of special concern, and so are careful attention to mechanical parts and the selection of the materials used for the conveyor.

LEAD POTS AND SALT BATHS

Lead pots, salt baths and similar baths of molten material are used to provide rapid and uniform heating at lower temperatures. This is possible since the heat transfer coefficients of a liquid in contact with a solid are relatively high compared with those attained at low temperatures, except when employing forced circulation of gases.

These molten baths must normally be operated at constant temperatures. They are generally fired by gaseous or liquid fuels, though electricity is also used. A steady input of heat is therefore essential but when they have been properly adjusted they should operate **continuously** with little attention. They cannot be readily shut off when the supply of work for treatment ceases, and it is necessary, therefore, for economical working, to provide a steady throughput of material to be provided, otherwise it is desirable to work for several days at a time and then shut down.

They have, however, disadvantages. The salt retained on the surface of the articles has a tendency to change the composition of the quenching bath. The molten content of the salt bath has a tendency to creep up the sides and over the lip and when in contact with the outer surface to cause severe corrosion of the material of the pot. Uneven heating, the local influence of the flame, temperature differences in heating up (with the resulting strains), the incidence of too sharp corners, may all contribute to cracking of the containers. Unless satisfactory materials are used for the pots their durability is reduced. In this respect too the disposition of the burners is an important factor, and there must be precautions against local overheating from this cause.



FIGS. 27, 28. Bogie type continuous furnace, fired by producer gas.

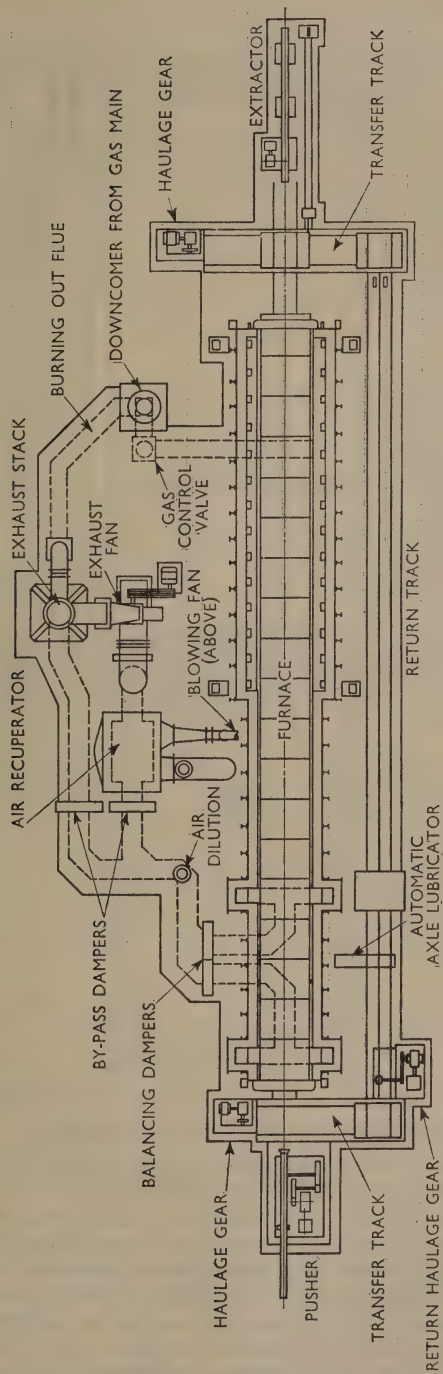


Fig. 28. Bogie type continuous furnace. Section through soaking zone.

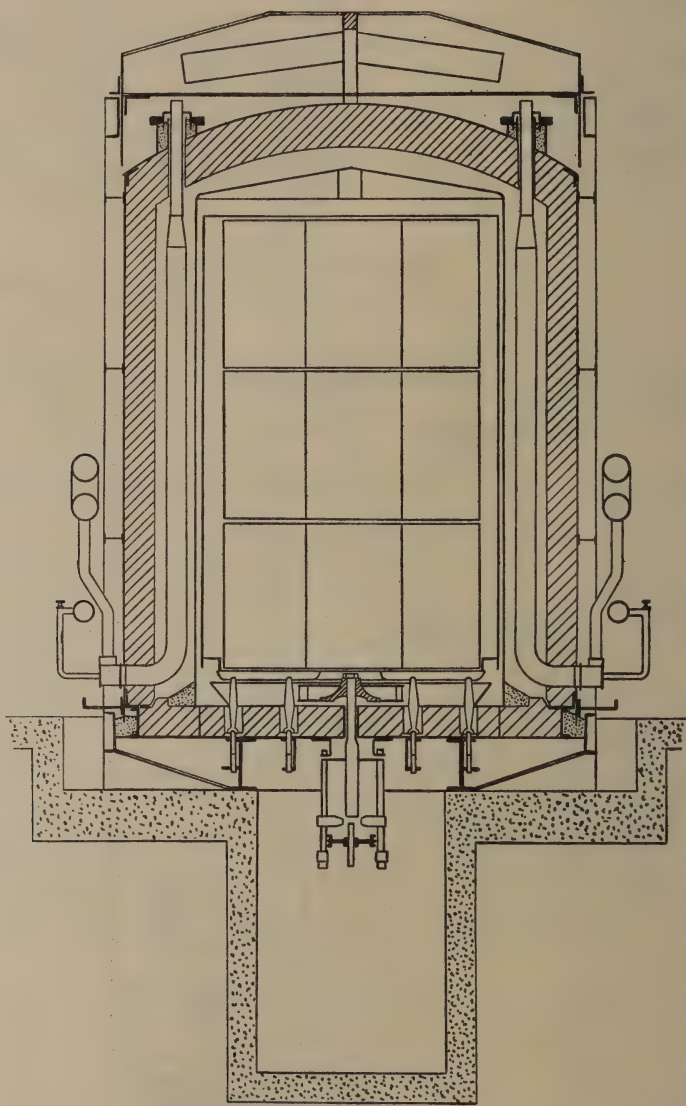


FIG. 29. "Top Hat" Furnace. For close annealing, with controlled atmosphere.

HIGH TEMPERATURE HEAT TREATMENT FURNACES

For the hardening of tools of high-speed steel, chamber furnaces, fired either by gas or oil, or electrically heated, are employed. The main requirement is rapid heating attained by the use of burners of adequate intensity. The waste gases from the finishing chamber are used in an upper chamber for the purpose of preheating. Temperatures are sometimes controlled visually since the hardening temperature is revealed by a change in the appearance of the scale on the tool, but the use of the optical pyrometer is recommended for certain and accurate control.

Recently high temperature salt baths heated electrically have been developed for these purposes, and they are capable of a high standard of scientific control by means of suitable instruments.

GAS EQUIPMENT

For many heating operations in the industrial furnaces described in the preceding sections, gas producers are used as the source of heating gas. The layout of a producer plant will be seen from Figs. 2, 3 in Chapter 18.

FURNACE CONTROL

Much has been said in the foregoing chapters regarding the practical measures that may be taken to ensure the efficient operation of furnaces. There remain, however, certain points which apply only to particular types. The following hints, not by any means exhaustive, may prove useful; others may be found in the various handbooks prepared by individual industries for their special purposes.

1. MELTING FURNACES

- (i) All melting equipment should be used to its maximum capacity.
- (ii) Where practicable the optimum rate of driving to give quick melting should be discovered by investigation and maintained.
- (iii) Control of combustion conditions and of draught are of special importance in high temperature furnaces.
- (iv) Advantage should be taken when rebuilding to establish construction on the lines of the best practice. The correlation of the changes made with the furnace performance systematically recorded assists in arriving at the most effective design for the practice applied.
- (v) Constant watch should be maintained on fuel supply, valves, dampers, flues, draught, sources of waste heat as in covers, doors, linings, and points of possible air inleakage.
- (vi) Instruments installed should be well maintained and used.

2. REHEATING FURNACES

- (i) Records of fuel consumption and rate of output should be systematically kept and studied in relation to varying shop conditions.
- (ii) Optimum rates of fuel consumption should be determined for the outputs required, and controls adjusted accordingly. Correct settings of valves and dampers may be marked for the use of the operators. The quickest heating is the most economical if practicable.
- (iii) Combustion conditions should be investigated and suitable controls applied.
- (iv) Balanced draught should be maintained.
- (v) All the known principles of good maintenance should be observed.

3. HEAT TREATMENT FURNACES

(a) *Batch Furnaces.*

- (i) The points indicated in Section 2 above apply in general.
- (ii) Furnaces should be charged, if practicable, to their optimum load.
- (iii) Periodic surveys of temperature uniformity assist in the ready detection of air inleakages.

(b) *Continuous Furnaces.*

- (i) The points in Section 2 above are applicable.
- (ii) Continuity of operation should be aimed at, and therefore work should be planned well ahead.
- (iii) When the programme calls for a shut down the lower temperature work should be undertaken at the end of a run.
- (iv) Precision temperature control attains economical use of fuel as well as quality of products.

(v) It is important to safeguard against the overheating of mechanical equipment such as conveyors since overheating of this equipment wastes fuel and causes risk of breakdowns and delays.

(vi) The net load should be kept as high as possible in relation to the gross load, since excessive heat abstracted in containers, trays and carriers represents a waste of heat.

(vii) Leaks from seals, defective brickwork and badly fitting doors should be regularly located and stopped.

(viii) If water-cooling is provided, the water passages should be kept clean to avoid local hot spots due to deposits.

(ix) Automatic gas control without damper control may be wasteful, as a furnace which is correctly balanced when "on gas" may pull air when "on by-pass", unless the draught is reduced. A loose-fitting butterfly valve may accordingly be provided in the waste gas flue and connected by linkage to the automatic gas control valve.

(x) Heavy gauge mild steel trays or containers may be replaced by light gauge special steel sheets with a consequent gain in heat conserved in the furnace.

VARIABLE FLOW OF HEAT IN FURNACES

The treatment of the subject of Heat Transmission in Chapter 9 has been based on the flow *in steady conditions*. Such conditions do not always exist in practice, and many problems arise in which the temperature varies. In furnace practice, particularly on questions relating to the flow of heat into the furnace structure and the charge, variable flow is encountered, which entails much more difficult methods than are required for the simpler problems of steady flow. The subject becomes so complicated that even by using the methods of higher mathematics only limited types of problem can be solved. Fortunately the problem has been considerably simplified for the practical man by the use of charts, derived from the particular solution of the Fourier conduction equation for the cases involved.

THERMAL DIFFUSIVITY

The physical property of the heated material which is important in considering variable flow is not the thermal conductivity, but the temperature conductivity, usually referred to as the "thermal diffusivity". As the charge in the furnace is heated there will not only be a flow of heat from layer to layer within the heated body, but also an absorption of sensible heat by the various layers of the body, and this will depend upon the specific heat and the density of the body. In short the temperature displacement, of which the thermal diffusivity, D , is a measure, must be inversely proportional to the specific heat of the material per unit volume.

The rate of temperature progression is greater the faster the temperature rise of the adjacent layer, and this temperature is in turn proportional to the amount of heat flowing in. The laws of heat flow define that this amount of heat is for a given temperature difference proportional to the thermal conductivity, k . The thermal diffusivity, D , is equal to

$$\frac{k}{\text{specific heat per unit volume}}, \text{ or } a = \frac{k}{c\rho}$$

when $k = \text{B.t.u./ft. hr. deg. F./ft.}$

$\rho = \text{lb./cu. ft.}$

$c = \text{B.t.u./lb. deg. F.}$

$a = \text{sq. ft./hr.}$

The cases that have been solved usually require that some specified and steady rate of heating is implied. Thus the surface of the solid body may be suddenly raised to a specific temperature, which never happens in practice,

but a result may be obtained of sufficiently approximate value to be of practical use. Alternatively a rate of heating may be applied to give a steady rate of temperature rise at the surface. This may again apply only approximately, but the results may be of value.

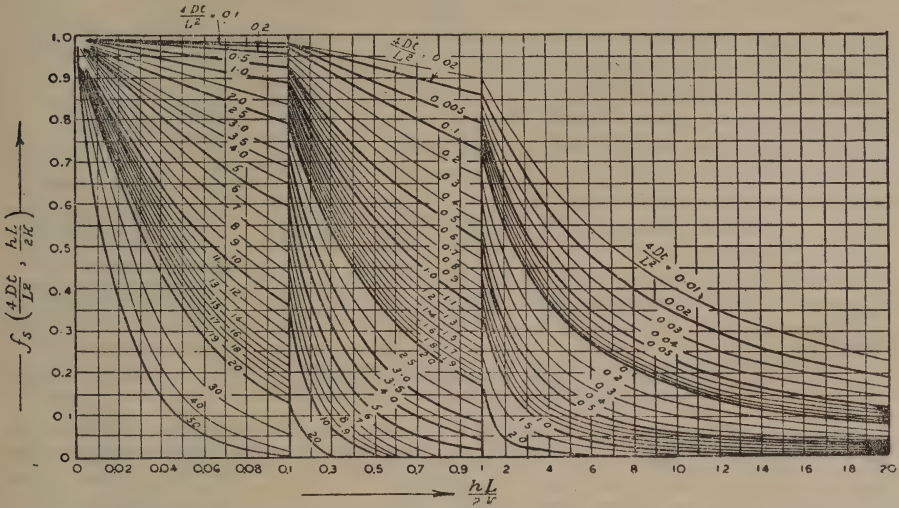


FIG. 30. Graphical calculation of rate of change of temperature of the surface of a wall of finite thickness in contact with a medium from which heat is being transferred to it (Gröeber).

(Reprinted by permission of the publishers (Chapman and Hall) from "Industrial Heat Transfer," by A. Schack).

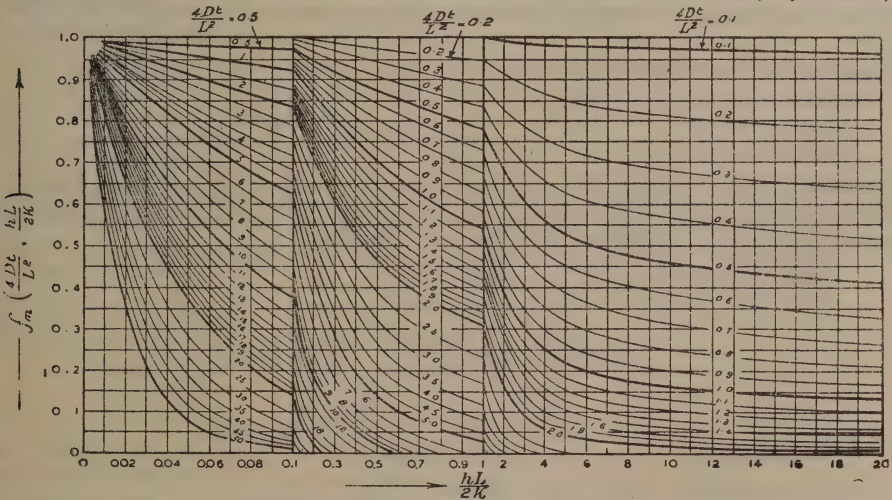


FIG. 31. Graphical calculation of the rate of change of temperature of the central plane of a wall of finite thickness in contact with a medium from which heat is being transferred to it. (Gröeber.)

(Reprinted by permission of the publishers (Chapman and Hall) from "Industrial Heat Transfer," by A. Schack).

By way of example, the data shown in Figs. 30 and 31 which refer to solutions obtained by H. Gröeber¹⁶ apply to a wall or plate of finite thickness in which the flow of heat is normal to the surface, as in large walls, slabs or plates. Any end effect introduces flow in more than one direction and then the problem becomes still more complicated.

The charts enable the problem of the slab or wall to be solved when the plate at an initial temperature, θ_1 , is placed in a heat transfer medium at a temperature, θ_2 . The other elements of the problem are:

L = thickness of the plate: feet.

t = time during which the slab is heated: hours.

a = thermal diffusivity of the material of the plate.

h = surface conductance of the slab: B.t.u./sq.ft.hr.deg. F.

k = thermal conductivity of the material of the plate:

B.t.u./sq. ft. hr. deg. F./ft.

θ = temperature at the point investigated after t hours, °F.

The equations applying may be expressed as follows:

$$\theta_s = \theta_2 + (\theta_1 - \theta_2) f_s \left(\frac{4at}{L^2} \cdot \frac{hL}{2k} \right) \quad \text{. . . . (Fig. 30)}$$

and

$$\theta_m = \theta_2 + (\theta_1 - \theta_2) f_m \left(\frac{4at}{L^2} \cdot \frac{hL}{2k} \right) \quad \text{. . . . (Fig. 31)}$$

where

θ_s = temperature at the surface of the slab

θ_m = temperature at the mid-plane of the slab.

The case of a wall heated from one side may be considered as equivalent to that of a slab of double the thickness, ignoring in the first approximation the character of the heat flow from the opposite surface, or alternatively considering it as a perfectly lagged wall.

The method will now be applied to a 9-inch firebrick wall, covered by 3 inches of insulating brick; it is desired to know the heat absorbed by the wall at the end of twelve hours if a temperature of 1,000° C. (1,832° F.) is suddenly applied to the inner face. The wall is initially at a temperature of 15° C. (60° F.). The surface conductance, $h=4$ B.t.u./sq.ft.hr.deg. F. The thermal properties of the firebrick may be assumed as follows:

$$\left. \begin{array}{l} k=0.75 \text{ B.t.u./sq.ft. hr. deg. F./ft.} \\ c=0.26 \\ \rho=115.4 \text{ lb./cu. ft.} \end{array} \right\} \text{whence } a=0.025 \text{ sq.ft./hr.}$$

The wall may be considered as equivalent to a slab 18 inches thick heated from two sides, the insulating brick being regarded for the purposes of a useful approximation as equivalent to a perfect insulator¹⁷.

$$\frac{4at}{L^2} = \frac{4 \times 0.025 \times 12}{(1.5)^2} = 0.53; \quad \frac{hL}{2k} = \frac{4 \times 1.5}{2 \times 0.75} = 4$$

$$\text{From Fig. 30 } f_s \left(\frac{4at}{L^2} \cdot \frac{hL}{2k} \right) = 0.16$$

$$\text{From Fig. 31 } f_m \left(\frac{4at}{L^2} \cdot \frac{hL}{2k} \right) = 0.535$$

whence temperature after twelve hours

at the surface,

$$\begin{aligned} \theta_s &= 1,832 + (60 - 1,832) (0.16) \\ &= 1,548.5^\circ \text{ F.} \end{aligned}$$

at the mid-plane
or interface in the
case chosen be-
tween the fire-
brick and the in-
sulating brick.

$$\begin{aligned} \theta_m &= 1,832 + (60 - 1,832) (0.535) \\ &= 883.5^\circ \text{ F.} \end{aligned}$$

The mean temperature of the firebrick is accordingly 1,216° F. and the heat absorbed after twelve hours per square foot of internal surface

=1,156 × heat capacity of the firebrick per deg. F.
=1,156 × 0.26 × 0.75 × 115.4 = 26,010 B.t.u.

In this example, the surface conductance depends upon the nature of the convective and radiative heating. In a furnace with a luminous flame, the value of the conductance, h, may rise as high as 24 B.t.u./sq. ft. hr. deg. F., and then the heating would be more rapid, the mean temperature at the end of twelve hours would rise to 1,486° F. (808° C.), and the heat storage to 33,400 B.t.u./sq. ft. of wall surface.

The experiments cited (*loc. cit.*) show that the insulation at the back of the firebrick would absorb less than 5 per cent. of this quantity of heat.

An alternative set of charts based on the work of H. P. Gurney and J. Lurie¹⁸ are given in Figs. 32 and 33 for a slab and cylinder respectively. The basis is similar to that of Gröber, except that the groups of variables are arranged differently and the charts are more easily read. The groups of non-dimensional variables resemble those applicable to the former diagrams, the main difference being that the value R is the half thickness of the slab and the radius of the cylinder.

$$\Delta = \frac{\theta_2 - \theta}{\theta_2 - \theta_1}, \quad m = \frac{k}{hR}, \quad \rho = \frac{r}{R}, \quad \tau = \frac{at}{R^2},$$

where r = the distance (feet) from the centre of the material to the point at which the temperature θ , after time t hours is required. τ is the "relative time." θ_1 is the initial temperature of the mass; θ_2 is the temperature of the heating medium.

Thus when $\rho = 0$, the centre temperature, θ_m , is obtained, and when $\rho = 1$, the surface temperature, θ_s , is given.

The use of the chart is shown by an example, in which it is required to determine the uniformity of temperature between centre and surface of a cylindrical steel bloom 24 inches in diameter, after periods of 4, 6, 8 and 10 hours heating. The furnace chamber is at 1,150° C. (2,100° F.), θ_2 , and the bloom on charging is at 500° C. (930° F.), θ_1 . The heating is to be considered to be uniform all round the mass, a condition which is not strictly applicable in practice but which has to be assumed for the purpose of the computation. The thermal constants of the material, and the surface conductance are to be taken as follows:

$h = 40, \quad k = 22, \quad a = 0.29$

whence

$\tau = 0.29t \text{ and } m = 0.55$

$\Delta_m = \frac{\theta_2 - \theta_m}{1,170} \quad \Delta_s = \frac{\theta_2 - \theta_1}{1,170}$

The following values of the temperature differences, $(\theta_2 - \theta_m)$ and $(\theta_2 - \theta_s)$ may be derived from values read from Fig. 33.

TABLE 00

t =	4	6	8	10
$\theta_2 - \theta_m$ ($\rho = 0$)	82	22	5	1.4
$\theta_2 - \theta$ ($\rho = 1$)	41	8	2	0.6
$\theta_m - \theta_s$	41	14	3	0.8

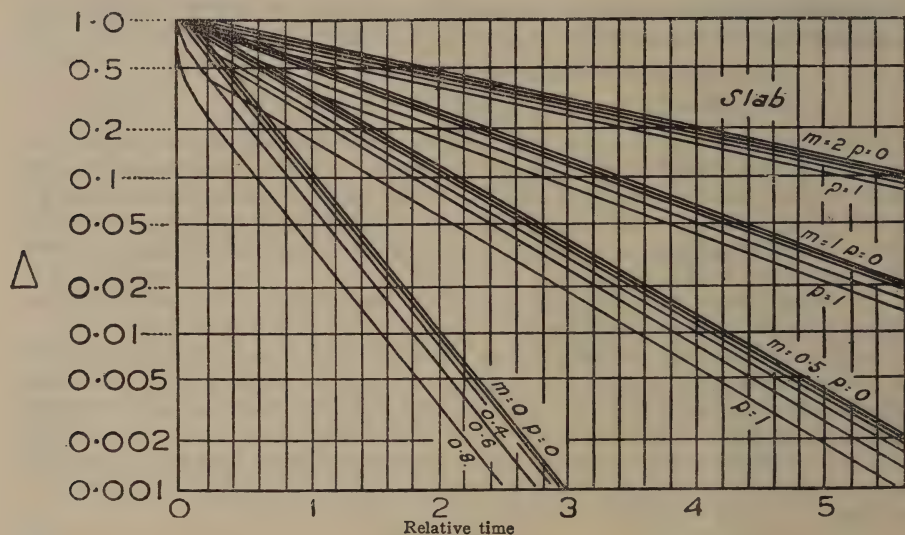


FIG. 32. Graphical calculation of the rate of heating of slabs.

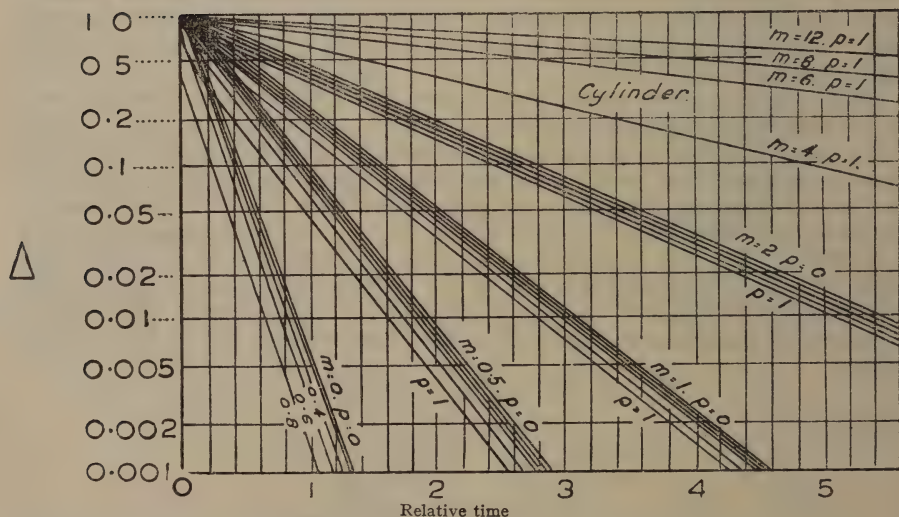


FIG. 33. Graphical calculation of the rate of heating of cylinders.

(Figs. 32 and 33 are reproduced from the paper by Gurnie and Lurie¹⁸, *J. Ind. Eng. Chem.*, XV, 1170.)

The time required in practice for heating such a bloom to a serviceable uniformity at the temperature stipulated would be of the order of 8-10 hours. There are the following differences between theoretical and practical conditions usually ruling. The furnace picks up heat gradually; it is not suddenly raised to the working temperature. There is always a gradient from hot gases to metal. Temperature distribution is not ideally uniform and heating is usually greater from one side. A uniformity of ± 5 deg. C. (± 9 deg. F.) must be regarded as very satisfactory and ± 10 deg. C. (± 18 deg. F.) as workable.

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CHAPTER 21

WASTE HEAT RECOVERY

THIS chapter does not deal with the recovery of heat by recuperators and regenerators as practised in metallurgical furnaces, coke ovens, and some gas plants. In those cases the heat is returned direct to the furnace normally in the pre-heated combustion air, sometimes in the pre-heated fuel gas also. The technique here discussed is that of heat recovery from the reject gases after they have left the regenerators or recuperators. Where regeneration or recuperation is not practised the gases go direct to the waste heat boiler as, for example, in non-regenerative carbonizing plants.

The flue gases finally rejected from any industrial furnace must inevitably leave at a temperature above that required by the material being treated at the point where the gases pass away. The sensible heat in the flue gases is used to create the required chimney draught where no heat recovery is practised but if the natural draught chimney is replaced by an induced draught fan, the heat gap between furnace outlet temperature and appropriate fan intake temperature represents heat that may be recoverable. Even after heat recovery, a chimney may still be used, e.g. as at coke ovens. Furthermore, the amount of heat extracted from the flue gases by regenerators may be so great that the outlet temperature is just high enough to provide the necessary draught in a chimney.

The primary purpose of regenerators is not to extract all possible heat from the gases in order to improve the overall efficiency, but to return sufficient heat to the combustion air and to the fuel gas to produce the temperature needed in the furnace. One example of this is the open hearth steel furnace, where the gases may leave the regenerators at a temperature of the order of 450–600° C. and will thus contain a good deal of heat that can be recovered and put to useful purpose. Furthermore, in the case of the open hearth furnace, the gases show considerable temperature peaks due to the heat of chemical reactions in the furnace itself.

Another example is the retorts used in the Gas Industry. In the case of horizontal and intermittent vertical retorts, the air required for combustion is pre-heated by recuperation. In continuous vertical retort practice, recuperation is not usual, all available waste heat being used for steam-power generation, air pre-heating being effected by cooling the bottoms of the retorts, etc., by air circulation. The producer gas is generally made from coke in producers using very little steam. In these conditions, every cubic foot of producer gas needs about 0.8 cu. ft. of air and yields 1.6 cu. ft. of total combustion products. There are thus 1.6 cu. ft. of outgoing products leaving the combustion chambers at 1,000–1,200° C.; where recuperators are used, there is less than half this volume of incoming air.

Even if the incoming air were heated to the temperature of the outgoing producer gas, the heat abstracted would be only half of that initially present; thus at least half of the total original heat in the flue gases leaving the settings is available for further recovery. In these circumstances waste heat boilers are used.

Some examples of the temperature of gases leaving furnaces of various types are given in Table 1.

Heat recoverable from flue gases

The heat recoverable from flue gases depends on the efficiency of the boiler, the quantity of the flue gases and the gas temperature drop through the boiler.

The theoretical heat recovery, H , can be calculated from the expression:

$H = Ws_w(t_1 - t_2)$ B.t.u. . . (1).

$H = Vs_v(t_1 - t_2)$ B.t.u. . . (2).

where W = weight of gases, in lb.

V = volume of gases; cu. ft. at 60° F. and 30 in. pressure.

s_w = mean sp. ht. of gases between t_1 and t_2 ; B.t.u. per lb. (1)

s_v = mean sp. ht. of gases between t_1 and t_2 ; B.t.u. per cu. ft. (2).

t_1 = temp. of gases entering the waste heat boiler; ° F.

t_2 = temp. of gases leaving the waste heat boiler; ° F.

TABLE 1
APPROXIMATE TEMPERATURES OF GASES LEAVING FURNACES

<i>Furnaces, etc.</i>	° F.	° C.
Nickel refining furnaces	2,500-3,100	1,370-1,700
Beehive coke ovens	1,950-2,300	1,070-1,260
Black-ash or black-liquor furnace	1,800-2,200	980-1,200
Copper reverberatory furnaces	1,650-2,000	900-1,090
Zinc refining furnaces	1,700-2,000	930-1,090
Heating and puddling furnaces	1,700-1,900	930-1,040
Copper refining furnaces:	500-2,200	260-1,200
Cement kilns:		
(Dry process)	1,150-1,500	620-810
(Wet process)	800-1,200	425-650
Open hearth furnaces		
(Producer gas)	850-1,100	455-595
Gas retorts (producers-gas-fired):		
(Regenerative)	840-1,110	450-600
(Non-regenerative)	1,470-1,830	800-1,000
Oil stills	900-1,000	480-540
Glass tanks	800-1,000	425-540

In practice there is a certain amount of loss from exposed surfaces which may account for about 5 per cent. of the total, so that the actual heat recovered is likely to be about 95 per cent. of the figures given by this calculation.

It will be seen that the higher the temperature of the incoming gases and the lower the temperature of the outgoing gases—i.e., the greater the value of $t_1 - t_2$ —the greater will be the amount of heat that should be recovered (see Table 2).

An example of this from gasworks practice is given in graphical form in Fig. 1, in which the gases result from the combustion of a producer gas of the following composition:

CO . . 25 per cent.
H₂ . . 8 " "
CO₂ . . 5 " "
N₂ . . 62 " "

The gas has been generated in a producer having a hot gas efficiency of 86 per cent. The flue gases leave the waste heat boiler at 230° C. (446° F.), the boiler operating at 160lb./sq. in.

In this field, particular attention is directed to two points:

- (a) the great effect of the boiler inlet temperature,
- (b) the very considerable effect of excess air used in the combustion of the gases.

It will be seen later in this chapter that if the excess air is introduced as a result of leakage after the combustion chamber, the effect is even more marked.

Some examples from industrial practice are given in Table 2. These are of course, individual examples and are to be regarded as illustrative only and not necessarily typical.

TABLE 2

<i>Furnace</i>	<i>Output</i>	<i>Fuel consumption</i>	<i>Gas Weight lb./hr.</i>	<i>Boiler Heating Surface sq. ft.</i>	<i>Entrance and exit gas temp. ° F.</i>	<i>Output lb. steam from and at 212° F. per hour</i>
Cement kiln 2 kilns per boiler	52 barrels per kiln per hour	103 lb. coal per barrel	195,280	15,330	1,225 429	26,800
Cement kiln 1 kiln per boiler	44 barrels per hour	100 lb. coal per barrel	58,224	4,688	1,485 422	9,300
Beehive coke ovens	2,600 lb. coal coked per hour	—	145,000	10,200	2,158 477	37,200
Horizontal gas retorts; 5 settings per boiler	75 tons coal carbonized per day	1,055 lb. coke per hour	17,736	1,339	1,225 425	2,330
Glass furnace	2,380 lb. batch per hour	2,850 lb. coal per hour	43,660	2,860	808 401	2,850
Malleable melting furnace	1.8 tons per hour	830 lb. coal per hour	25,150	2,620	1,650 430	4,700
Puddling furnace	758 lb. per hour	857 lb. coal per hour	20,000	1,880	1,977 501	4,900
O.H. steel furnace	75 tons	550 lb. coal per ton	61,000	5,830	1,040 460	9,200
O.H. steel furnace	59 tons	47 gall. oil per ton	83,720	4,220	1,065 500	7,600
Steel reheating furnace	No record	112,760 cu. ft. gas per hour	80,757	5,840	1,445 545	1,200

Principles of Heat Recovery in Waste Heat Boilers

A primary distinction between fuel-fired boilers and waste heat boilers is that the heat transmission in the former is largely by radiation, whereas in the latter lower temperatures are involved and heat transmission is essentially by convection or contact. The differences between these two processes will have been appreciated from Chapter 9 (Heat Transmission), from which it will also be seen that high temperatures, particularly where there is a solid fuel bed or there are luminous flames, radiation is by far the more rapid process.

With gases making contact with the heating surface of ordinary boilers at 1,250° C. (2,280° F.) and leaving at 250° C. (480° F.) about 70 per cent. of the evaporation is due to radiation and the remaining 30 per cent. to convection, or contact between the gases and the boilers surfaces¹. From the principle that radiation depends upon the difference between the fourth powers of the absolute temperatures of the source of heat and of the cooler surface receiving the heat (Chapter 9), it has been calculated¹ that 900° C. and 450° C. the percentages of heat transferred by radiation and convection respectively are:

Temperature of incoming gases	1,250° C.	900° C.	400° C.
	(approx.) (2,280° F.)	(1,650° F.)	(750° F.)
Percentage of heat transferred by radiation...	70	24.7	3.6
Percentage of heat transferred by convection	30	75.3	96.4

Surfaces merely exposed to gases do little work with low temperature heat. Intimate contact must be obtained so that the surface is scrubbed by the

gases. In a modern waste heat boiler the design is such as to give that intimate scrubbing contact between gas and heating surface that is essential for reasonably effective heat transfer.

From the laws of conduction and convection (Chapter 9)

- (a) The transfer of heat by convection is slow compared with that by radiation.
- (b) With streamline flow there is a layer of flue gas of very low conductivity between the main stream of gas and the boiler plate (Chapter 10, Flow of Fluids), causing a serious hindrance to the transmission of heat.
- (c) The thickness of the film can be decreased by increasing the rate of flow of the gases so as to render it turbulent.

From the discussion in Chapter 9 on Heat Flow parallel to and across tubes, it is obvious that in the case of a water-tube boiler an arrangement whereby the gases travelling across the tubes provides the best design for rapid heat transfer.

There are, however, practical reasons why the fire-tube type of boiler, in which the gas is passed through a number of tubes of the order of $1\frac{3}{4}$ – $2\frac{1}{2}$ in., is more generally adopted.

The essence of contact heating is to break up the gas stream and force the particles to give up their heat by molecular contact. This is effected in various ways according to the basic type or design of the waste heat boiler :

- (a) In water-tube boilers, by suitable disposition of the tubes and the baffling in order to promote gas flow across the tubes. This applies also to the thimble-tube design of boiler.
- (b) In fire-tube boilers, by operating at high gas velocities which give turbulent flow, with a high degree of molecular impact on the tube walls.
- (c) Special fire-tube designs where, instead of depending on turbulent flow created by velocity, contact is achieved by means of retarders, or by curvature of the tubes, this curvature having the effect of throwing the gas particles against the tube walls at each change of direction.

Draught

The waste heat boiler is ancillary to the furnace to which it is attached. Consequently its operation must create no effect detrimental to the operation of that furnace.

The quantities of gases dealt with by a waste heat boiler are very much greater in proportion to steam output than the quantities in a fuel-fired boiler; the draught required is, therefore, higher by the standards of normal boiler operation, often four or five times that usual in a fuel-fired boiler in industrial practice, after allowing for the draughting of the furnaces, recuperators or regenerators, and for the considerable lengths of tube work commonly involved.

Waste heat boilers also impose a relatively high resistance to the flow of gases, the gas velocity being increased to cause a high degree of turbulence. The pressure drop in fire-tube boilers is seldom less than 2 in. w.g., and may be as much as 4 in. The fact that with the installation of waste heat boilers induced draught is necessary may have the advantage that the additional draught improves the working of the furnace.

In considering the question of draught, it must not be forgotten that furnaces, particularly those fired by clean gas, will remain in their original condition and require about the same amount of draught throughout their working life if the walls are kept gas-tight. Other furnaces, particularly those burning solid fuel or uncleaned producer gas, will become partly choked with dust, particularly if regenerators are used; the draught required may therefore increase with increasing age of the furnace. This should be taken into account

when installing the fans for the waste heat boiler.

There is sometimes an appreciable vertical distance between the point at which the hot products of combustion leave the furnace and the point where they leave the regenerators. This may easily amount to 25ft. in a furnace of quite moderate size, and as, during their passage from the furnace to the regenerator outlet, the average temperature of the gases may be over 1,000° C. (1,830° F.) it will be realised that in this part of the system there exists an appreciable chimney effect, about 1in. w.g. in this instance, which the flue gases in the chimney have to overcome in addition to the normal frictional resistance of the plant.

Air Inleakage

The quantity of heat that will be recovered in a waste heat boiler depends on the initial temperature of the gases. If this initial temperature is lower, the rate of heat transfer will be reduced. The size of a boiler is calculated, in the first place, on a given inlet temperature and a given outlet temperature. If the gases are diluted with cold air, they may still carry the same total quantity of sensible heat (in diluted form) through the boiler, but since the temperature drop will be less the efficiency of the boiler will diminish.

Because of the high draught needed, a waste heat boiler is under considerable suction; trouble is frequently encountered in the operation of water-tube waste heat boilers due to air infiltrating through the comparatively extensive surfaces associated with this type of boiler. Conditions in this respect are greatly improved by the practice of encasing the boiler brickwork, but as the boiler steam output is already low in relation to the size—and cost—of the boiler (in comparison with normal boiler practice) the effect on the economies of the installation may require consideration.

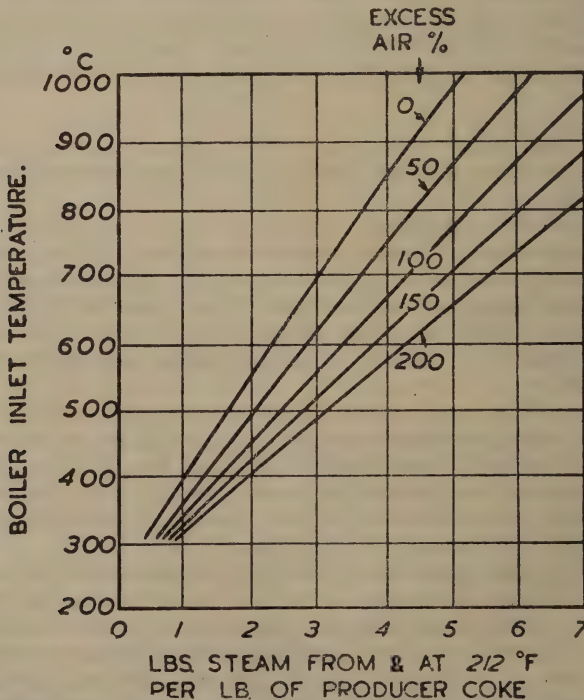


FIG. 1. Heat content of the flue gases derived from a furnace heated by a coke-fired producer. (Reproduced by permission of Spencer-Bonecourt-Clarkson Ltd.)

The ingress of cold air:

- (a) Lowers the temperature of the gases, increases their volume and reduces the potential evaporation owing to the greater volume at a given outlet temperature of the gases passing to atmosphere.
- (b) Increases the load on the induced draught fan, often to the extent of causing it to fail to give the requisite pull at the furnace.
- (c) Causes boiler leakage, due to local cooling effects.
- (d) If unburned constituents have passed over in the waste gas flue—having failed to ignite before entering the boiler—local gas explosions occur in the boiler setting, providing the ignition temperature can be reached at a point of air ingress.

The effect of air infiltration depends upon the place where the air enters. If the additional excess air is admitted into the furnace proper and thus heated to a high temperature, the result is an increase in the amount of heat recovered in the waste heat boiler for a defined inlet temperature, as shown in Fig. 1.

On the other hand, if the air enters after the furnace, it serves only to dilute the flue gases and lower their temperature, with resultant lower heat recovery potential. Thus, in a waste heat boiler operating with an outlet temperature of 230°C . (446°F .) the addition, by infiltration, of 200 cu. ft. of air at atmospheric temperature, into 800 cu. ft. of furnace gases at 500°C . will result in a volume of 1,000 cu. ft. of mixed gases at a temperature at approximately 400°C . (750°F .), all volumes being measured at atmospheric temperatures.

It is true that the total quantity of sensible heat is unaltered, but as 25 per cent. more gas has to be rejected to the chimney, at approximately the original outlet temperature— 230°C . (446°F .)—greater heat losses are thereby incurred; steam production is reduced.

The effect of infiltration of air into the flue can be clearly shown by an exaggerated example. If every 800 cu. ft. of furnace gases at 500°C . (932°F .) were mixed with 1,000 cu. ft. of infiltrating cold air at atmospheric temperature, the temperature of the resulting 1,800 cu. ft. of mixed gases would be about 220 – 230°C . (420 – 446°F .), and the amount of steam raised would be practically nil.

Not only is "flue infiltration" entirely detrimental to the boiler by causing reduced steam output but the fan power necessary to handle the increased volumes of gas through the system will increase. For any boiler once installed, the draught loss—and hence the fan pressure head—will vary as the square of the rate of gas flow; as the fan power is the product of the fan pressure head and the volume moved, the power required will vary as the cube of the gas flow. A 25 per cent. increase in the volume passing through the boiler would thus necessitate a 95 per cent. increase in fan power. If, as may well happen, the fan motor is unable to develop the additional power required, the effective draught on the furnace regenerators will fall off, to the detriment of furnace operation, until the air infiltration is stopped.

The infiltration of air in regenerators is yet another aspect of this problem, because here the air will abstract heat from the regenerators and will thus be itself further heated. The resulting temperature of the mixed gas and air will thus be even higher than for the case just considered.

The primary tendency of infiltrating air is to cool the hot waste gases; this simultaneously results in the cooling of the regenerator checkers, with a consequential cooling effect on the fuel gas, and on the combustion air, and thus ultimately on the furnace temperature. The furnace operator would correct this by supplying more gas and more air to the furnace, the increased volume of hot flue gases then overloading the regenerators. The result might even be

a rise in the waste heat gas temperature at the outlet. Clearly, the heat required to bring the infiltrated air up to the flue gas temperature cannot be supplied from the flue gases, and must be supplied indirectly from the fuel gas, the only source from which additional heat can be supplied. Regenerator infiltration thus results in more steam being raised, if a waste heat boiler is attached, though naturally the inefficiency and cost of generating steam by gasifying extra fuel in producers in order to supply extra quantities of low grade heat to the boiler renders the whole process far from economic.

If the boiler was originally designed to deal with the gases from a leaky regenerator, and the regenerator is subsequently made gas-tight in order to improve the efficiency of the furnace, the waste heat boiler may well become uneconomical. Its efficiency will suffer on account of the fact that all fixed radiation and convection losses—already rather significant in view of the comparatively small steam output from a fairly bulky boiler—will have to be subtracted from a reduced heat input, although themselves unchanged. The condition of the furnace and of its ancillary apparatus must therefore be carefully considered before a waste heat boiler is installed.

FEED WATER TREATMENT FOR WASTE HEAT BOILERS

The difficulties of securing an adequate rate of heat transmission by convection and conduction only, due to relatively low temperature differentials, are such that resistance to the flow of heat should be eliminated as far as possible. It is therefore necessary, for the efficient operation of waste-heat boilers, that the feed water be softened as completely as possible so that the amount of scale deposited on the heating surface shall be reduced to a minimum.

In this connection it is relevant to refer to the wide field for Waste Heat Recovery in the chemical industries where the subject is receiving rapidly increasing consideration. In this particular field higher pressure installations are predominating. As is emphasized in Chapter 16 the subject is a highly technical one and particular attention should be paid to the manufacturers' recommendations regarding feed water treatment.

TUBE CLEANING

It is important to keep the tubes of waste heat boilers clean partly in order to prevent any further resistance to the flow of heat and partly because the deposition of dust will cause serious loss of draught.

Among the methods that have been used in fire-tube boilers are the introduction of wood chips or coke breeze into the gas inlet box; these are swept through the boiler and exert a scouring influence. If a tube is badly blocked, the velocity of flow will not be sufficient to sweep the scouring material through. The condition of that tube will then be worse rather than better; only the less contaminated tubes will be cleaned, consequently the method cannot be generally recommended. The usual practice is to clean the tubes with a wire brush (or preferably a scraper head cleaner) through cleaning holes in the gas outlet box of the boiler. This operation should be carried out at least once per week.

In the case of water-tube boilers soot blowers, and in special cases rapper gear, are adopted. The already high rate of gas flow through the tubes of fire-tube boilers clearly makes the use of soot blowers generally ineffective.

It should be realized that tube cleaning may be regarded as a palliative rather than a remedy; consequently attention should be paid to the disposition of the heating surfaces so as to ensure, as far as possible, that they remain clean. One arrangement achieving successful results in the case of an open-hearth furnace consists of parallel pitch pendant heating surfaces equipped with mechanical wrappers. Soot blowers are not provided to the banks.

SUPERHEATERS

Superheaters are in general use in connection with waste-heat boilers. In fire-tube units they are of necessity situated in the boiler intake chambers; for waste gases up to 700° C. (1,290° F.) they are set in the flow of gases, but above this temperature they must be suitably protected from the gas stream flow and arranged for radiant heat absorption, in the interest of protecting the tube material. For these higher temperatures the rate of flow of steam through the superheater must be sufficient to prevent unduly high metal surface temperatures. With a correctly designed assembly arranged for radiant heating this arrangement is entirely effective in an intake chamber with the temperature as high as 1,100° C. (2,015° F.).

Water-tube boiler designs admit of the superheater being placed in an intermediate position within the boiler tube bank, so that its position can be chosen without it being exposed to radiation, and thus minimise the risk of overheating.

LIMITATION OF EXIT GAS TEMPERATURES

If a boiler is working at 160 lb./sq. in. the temperature of the water will be 371° F. ; it is clear that the gases must leave the boiler at a temperature equal to this figure plus an amount depending on the efficiency of heat abstraction in the boiler.

The difference between the boiler water temperature and the gas outlet temperature will usually be of the order of 80° F., so that the gas exit temperature for a boiler working at 160 lb. pressure will be about 450° F. As the gas inlet temperature may be only 1,000° F., it will be apparent that only 55 per cent. of the heat contained in the gas at the inlet can produce steam in the boiler, even if all radiation and convection losses were to be eliminated. In normal circumstances it is undesirable to allow the temperature of the exit gases to fall below 450° F. (230° C.) because experience shows that at lower temperatures the fan casing, outlet duct and neighbouring steel work may be seriously and rapidly corroded, depending on the SO₂ and SO₃ content of the gases, unless special precautions are taken.

ECONOMISERS

The use of economisers is subject to the limitations mentioned in the preceding section. Owing to the greater financial return resulting from waste heat recovery practice when fuel prices are high the use of economisers with larger units is becoming more general, especially where the higher steam pressures are adopted for power production—i.e. where the boiler outlet gas temperature is raised owing to the influence of the higher saturated steam temperature. Such economisers are often of the extended surface type in order to keep them compact, an arrangement normally calling for a higher gas draught than obtains with plain tubes.

BOILER EFFICIENCY

The efficiency of a waste heat boiler can be expressed in several ways. In a report² issued by the Iron and Steel Institute in 1935, there is a record of the results of an analysis of the working of a waste heat boiler installation. The performance of a boiler operating on a 50-ton open hearth furnace was given as in Table 3.

While for practical and economic estimates the data provided in this Table are used, the boiler efficiency is a factor of importance. The overall efficiency is the ratio of the effective output to the total heat input, i.e.

$$\frac{\text{Heat absorbed by steam} \times 100}{\text{Total heat in gas at inlet}} \text{ per cent.}$$

Substituting in this fraction the appropriate figures from Table 3 the efficiency is found to be $(35.29 \times 100 / 115.03)$ i.e. 30.7 per cent.

This is very low in comparison with normal boiler efficiencies but in this case the boiler was too large for the quantity of gases passing through it and better

TABLE 3
PERFORMANCE OF A WASTE HEAT BOILER

Size of boiler	18 ft. \times 9 ft. diameter.
Heating surface	3,593 sq. ft., composed mainly of 2 in. OD. fire-tubes.
Gas temperatures :	
(a) Inlet	452° C. (851° F.)
(b) Outlet	222° C. (431° F.)
Total heat in gas :	
(a) Inlet, above 60° F.	115.03 therms per hour.
(b) Outlet, between boiler water temperature 183° C. (362° F.) and 60° F.	58.14 therms per hour.
Total heat given to steam	35.29 therms per hour.
Heat loss in blow-down	0.19 therms per hour.
Other losses from boiler	13.30 therms per hour.
Total heat given up by gases to boiler	48.78 therms per hour.

<i>Evaporation</i>	<i>Actual lb.</i>	<i>Equivalent lb.</i>
Evaporation per hour	3,208	3,740
Evaporation per lb. of coal	1.75	2.05
Evaporation per ton of ingots	821	958

results can normally be expected. Actually the efficiency of heat transfer in this boiler was extremely good, as is shown by the fact that the gases were cooled to a temperature only 40° C. above that of the water in the boiler, and by the ratio:

$$\frac{\text{Heat absorbed by steam}}{\text{Heat given up by gases in boiler}} = \frac{35.29}{48.78} = 72.3 \text{ per cent.}$$

The coldest heat-absorbing surface must be at a temperature at least as high as that of the water in the boiler, the saturation temperature corresponding to the boiler pressure. The most efficient boiler possible, perfectly insulated and working with perfect heat transfer across the heating surfaces, could only reduce the gases to this temperature.

The true indication of the performance of the boiler under trial, therefore, is the ratio of the overall efficiency (30.7 per cent.) to the efficiency of a perfect boiler working under the limitation described above. The (available) efficiency of a perfect boiler is the ratio :

$$\frac{\text{Available heat in gas above boiler water temperature}}{\text{Total heat in gas at outlet}} = \frac{115.03 - 58.14}{115.03} = \frac{56.89}{115.03} \text{ i.e. } 49.4 \text{ per cent.}$$

The results were expressed in the report (*loc. cit.*) in the form of a diagram, Fig. 2.

Table 4, taken from Gas Works Practice, and Table 5, taken from Steel Works Practice, may be cited in illustration of actual operating results. The heat recovered as steam was measured in these tests but in order to show the order of magnitude of the losses the radiation loss has been assumed to

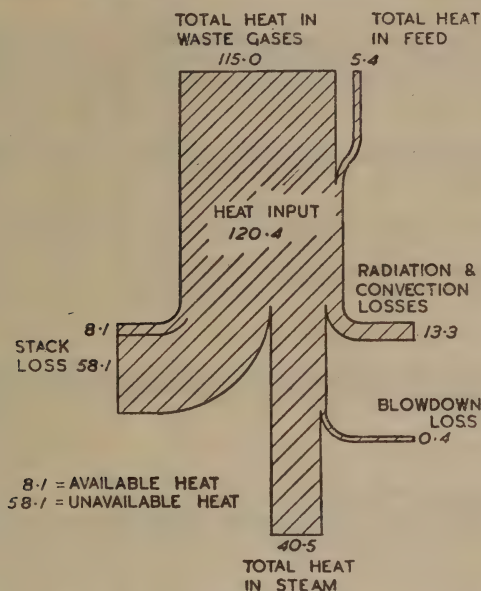


FIG. 2. Heat distribution diagram for a waste heat boiler.

(From the Second Report of the Iron and Steel Industrial Research Council, "Waste Heat Boilers in Open Hearth Practice.")

be 5 per cent. of the input heat, thus enabling the heat loss in the stack gas to be calculated by difference. The quantity of fuel fed to the producers was measured. From this account, and using the results of the analysis of the waste gases (for CO_2 and O_2) the actual weight of gas entering the boilers was calculated. This calculation, it should be noted, involves an arbitrary factor for the heat losses in the producer based on actual practical experience.

It is of great importance to reduce to a minimum surface losses both in the boiler and in the flue system conveying gases to the boiler. Frequently, as for example in a multiple bench of retorts or when a single boiler operates on the gases from a number of furnaces, the collecting flue system is of considerable length. Unless heat losses are carefully guarded against, a very large amount of the total heat available for steam raising can be dissipated from these gas ducts before the boiler is reached. Where flues have to be sited in the open they should be steel-cased and provided with the appropriate insulating lining. Properly hooded dampers are essential in all cases.

Another source of loss in flue systems that are carried below ground is that due to water—either water in the ground cooling the flues by contact, or water soaking into the flues.

It will be appreciated that waste combustion gases, rating per unit of heating surface is low compared with a fuel-fired boiler under equivalent gas weight flow conditions; hence for a given output the proportional loss from the boiler is high compared with ordinary boiler practice. To counteract this, it is essential to design waste heat boilers to be as compact as possible, in order to reduce surface to the minimum.

Effect of Intermittent Operation

If the flow of flue gases fluctuates considerably, the rate of steam generation will be subject to similar fluctuations. Steam from other boilers on the range may pass into the waste heat boiler during these periods, so the boiler will be condensing steam, from other sources, that has been made by the expenditure of coal.

TABLE 4
TYPICAL SETS OF TEST FIGURES: WASTE-HEAT BOILERS OPERATING IN CONJUNCTION WITH CARBONIZING PLANTS.

1	Gasworks .. .. .	..	..	..	..	..	..	A	B	C	D	E	F	G	H
2	Type of retorts .. .. .	..	..	..	..	..	..	Continuous verticals	Continuous verticals	Continuous verticals	Continuous verticals	Chambers	Horizontal	Horizontal	Horizontal
3	Coal carbonized per day .. .. .	..	..	..	..	..	..	130	155	140	24	135	184	93	48
4	Producer fuel, coke per hour .. .. .	..	..	..	..	..	..	1,820	2,240	1,950	403	1,860	2,020	1,300	715
5	(4) as percentage of (3) .. .. .	..	..	..	..	..	..	15	15.4	15	18	14.8	11.8	15	18
6	Net calorific value of fuel per lb. .. .. .	..	..	..	..	..	..	12,150	12,100	12,300	12,100	12,000	12,000	11,900	12,000
7	Temperature of gases at boiler inlet, T_1 .. .. .	..	..	..	..	..	..	760	890	730	890	800	490	560	480
8	Temperature of gases at boiler outlet, T_2 .. .. .	..	..	..	..	..	..	220	230	220	230	220	215	220	200
9	CO ₂ content of waste gases at boiler inlet .. .. .	..	..	..	..	..	..	13	15.4	12	12.5	13.5	10.9	11	10.5
10	Excess air equivalent of (9) .. .. .	..	..	..	..	..	..	90	50	115	100	50	143	105	165
11	Number of boilers under test .. .. .	..	..	..	..	..	..	2	1	1	1	1	1	1	1
12	Total boiler heating surface (H.S.) .. .. .	..	..	..	..	..	..	2,440*	3,400	3,200	600	2,000	4,250	2,000	1,220
13	Duration of test .. .. .	..	..	..	..	..	..	24	24	48	12	12	168	96	24
14	Average steam pressure .. .. .	..	..	..	..	..	..	119	118	110	115	118	115	88	95
15	Saturated steam temperature, T_s .. .. .	..	..	..	..	..	..	350	349	344	347	349	347	337	335
16	Superheat .. .. .	..	..	..	..	..	..	177	176	173	175	175	170	170	168
17	Feed temperature, boiler inlet .. .. .	..	..	..	..	..	..	120	150	95	Nil	Nil	210	200	125
18	Evaporation per hour, actual .. .. .	..	..	..	..	..	..	8,040	9,650	8,900	90	60	150	170	165
19	Evaporation factor .. .. .	..	..	..	..	..	..	1.15	1.25	1.13	1.17	1.20	1.23	1.20	1.165
20	Evaporation per hour, from and at 212° F. .. .. .	..	..	..	..	..	..	9,250	12,050	10,050	2,100	8,400	5,960	4,500	2,150
21	Evaporation sq. ft. H.S./hr. from and at 212° F. .. .. .	..	..	..	..	..	..	3,79	3,55	3,15	3.5	4.2	1.4	2.25	1.76
22	Evaporation per lb. of fuel, from and at 212° F. .. .. .	..	..	..	..	..	..	6.08	5.30	5.15	5.2	4.51	2.95	3.46	3.0
23	Mean heat transmission B.t.u./hour/sq. ft. H.S. B.t.u. .. .. .	..	..	..	..	..	..	3,650	3,430	3,040	3,380	4,055	1,350	2,175	1,700
24	Fan drive .. .. .	..	..	..	..	..	..	Turbine	D.C. motor	Turbine	Back pressure turbine	D.C. motor	Compound engine	Single cylinder engine	Single cylinder engine
25	Total fan horse-power .. .. .	..	..	..	..	..	..	17.5	16	15	2	19	14	9	5.5
26	Steam equivalent of (25), lb. per hour actual .. .. .	..	..	..	..	..	..	Regenerated	400	Regenerated	Exhausting to settings	455	Regenerated	Regenerated	Regenerated
27	(26) as percentage of (18) .. .. .	..	..	..	..	..	..	—	4.15	—	—	6.5	—	—	—
28	Extraction efficiency, i.e., $\frac{T_1 - T_2}{T_1 - T_0} \times 100$ .. .. .	..	..	..	..	..	..	92.5	92.5	91.7	91	93	87.5	87.2	90
29	Calculated evaporation from and at 212° F. per lb. of producer fuel .. .. .	..	..	..	..	..	..	4.8	5.1	5.0	5.0	4.3	2.85	3.37	2.9
30	Percentage difference between (22) and (29) .. .. .	..	..	..	..	..	..	+5.5	+4.4	+2.9	+3.85	+4.65	+2.6	+3.3	+3.3
31	Method of measuring boiler evaporation .. .. .	..	..	..	..	..	..	meter	meter	meter	meter	meter	meter	meter	meter
32	Total heat per lb. of producer fuel .. .. .	..	..	..	..	..	..	12,150	12,100	12,300	12,100	12,000	12,000	11,900	12,000
33	Heat delivered to combustion chambers at 86 per cent. efficiency .. .. .	..	..	..	..	..	..	10,400	10,400	10,600	10,400	10,300	10,300	10,250	10,300
34	Heat in gases entering boiler(s) .. .. .	..	..	..	..	..	..	7,010	7,010	7,000	7,140	6,000	5,080	5,500	4,980
35	Heat as steam .. .. .	..	..	..	..	..	..	4,850	5,200	4,975	5,025	4,360	2,850	3,340	2,900
36	Steam as percentage of total heat in producer fuel—see (35) and (34) .. .. .	..	..	..	..	..	..	40	43	40.3	41.5	36.5	23.75	28	24.2
37	Steam as percentage of heat in waste gas flue—see (35) and (34) .. .. .	..	..	..	..	..	..	72	74.25	71	70.4	72.7	56	61	58.2

NOTE.—(33) to (35) all calculated per lb. of producer fuel.

* 2 Boilers.

TABLE 5

TYPICAL SETS OF TEST FIGURES: WASTE-HEAT BOILERS OPERATING IN CONJUNCTION WITH STEELWORKS FURNACES.

Steelworks					Open hearth furnaces				Soaking pits	
					A	B	C		D	E
1	No. of furnaces tested	..	..	..	Four	One	One		Four	Four
2	Weekly capacity (total)	..	..	..	2,762	950	510		2,100	2,500
3	Hours in gas per week	..	..	..	149	150	144		136	128
4	Average steel/hour	..	..	..	18.6	6.33	3.55		15.4	19.5
5	Coal to producers/hr.	..	..	..	98	28.4	18		24.2	31
6	Coal/ton of steel	..	..	..	5.27	4.5	5.1		1.57	1.59
7	Net C.V. of coal per lb.	..	..	..	12,200	13,000	12,000		12,200	13,000
8	Duration of test	..	..	..	96†	100	96		96	96
9	Total H.S. of boilers	..	..	..	17,000	4,250	3,200		5,000	4,800
10	Mean inlet temperature T_1	..	..	..	551	595	475		475	565
11	Mean outlet temperature T_2	..	..	..	230	250	232		235	230
12	Mean CO_2*	..	..	..	7.6	10.3	7.0		8.5	10.2
13	Excess air corresponding to (12)	..	..	..	225	125	250		185	125
14	Steam pressure	..	..	..	160	250	155		160	160
15	Corresponding temperature to (14) T_s	..	..	..	370	406	368		370	370
16	Superheat	..	..	..	188	207	187		188	188
17	Feed temperature	..	..	..	115	125	55		105	131
18	Evaporation factor	..	..	..	160	120	180		160	122
19	Steam per hour, actual	..	..	..	1.17	1.23	1.11		1.16	1.22
20	Steam per hour, from and at 212° F.	..	..	..	32,000	7,800	5,000		5,600	8,300
21	Steam per lb. of producer coal from and at 212° F.	..	..	..	37,500	9,600	5,550		6,500	10,100
22	Steam per ton of steel from and at 212° F.	..	..	..	3.4	3.0	2.75		2.9	2.4
23	Steam per sq. ft. of H.S. from and at 212° F.	..	..	..	2,000	1,515	1,560		423	519
24	Equivalent of (22) as boiler coal at 8 lb. steam per lb. coal	..	..	..	2.2	2.26	1.74		1.3	2.1
25	Net coal consumption per ton of steel, i.e. (6) less (24)	..	..	..	2.24	1.7	1.74		.47	.58
26	Percentage fuel saving $\frac{T_1 - T_2}{T_1 - T_a} \times 100$	..	..	..	3.03	2.8	3.36		1.1	1.01
27	Boiler extraction efficiency $\frac{T_1 - T_2}{T_1 - T_a} \times 100$	..	..	..	42.5	37.8	34.0		30.0	36.5
28	Fan h.p.—boilers and furnaces.	..	..	..	88.5	89	84.5		83.5	88.5
29	Steam equivalent of (28) at works power house	..	..	..	115	35	25		25	32
30	(29) as percentage of total steam	..	..	..	1,900	525	400		430	480
31	Calculated evaporation per lb. of producer fuel	..	..	..	5.08	5.5	7.2		6.6	4.75
32	Percentage error between (21) and (31)	..	..	..	3.5	2.97	2.7		2.3	2.84
33	Percentage of total heat in fuel, recovered as steam	..	..	..	-2.95	+1.0	+1.82		+2.0	+2.0
34	Method of measuring evaporation	..	..	..	27.0	22.3	22.0		19.0	21.5
35	Remarks	..	..	..	Summary of two separate tests—each on 2 units	One of 6 boilers, on open hearth plant	One of 6 boilers, on open hearth plant		Meter	Meter

* CO_2 readings taken during reaction periods of Melting Furnaces rejected. † Two periods of 48 hours each.

ECONOMICS OF WASTE HEAT BOILERS

The efficiency of waste heat recovery is relatively low because of the comparatively small temperature drop through the boiler. The following figures, based on the assumption that the various losses (excluding flue gas loss) are 5 per cent. of the inlet heat, and that the outlet temperature is 450° F., indicate the general trend of recovery and its dependence on the outlet temperature. All figures are based on 1,000 lb. of flue gases, of specific heat 0.25 B.t.u. per lb.

TABLE 6
INFLUENCE OF FLUE GAS OUTLET TEMPERATURE, RELATIVE TO
INLET TEMPERATURE, ON WASTE HEAT RECOVERY

<i>Inlet temp.</i> ° F.	<i>Outlet temp.</i> ° F.	<i>Heat in gas :</i> <i>therms</i>	<i>Losses :</i> <i>therms</i>	<i>Heat in</i> <i>chimney gas :</i> <i>therms</i>	<i>Heat</i> <i>recovered :</i> <i>therms</i>
2,000	450	4.85	9.24	1.12	3.49
1,000	450	2.35	0.12	1.12	1.11
600	450	1.35	0.07	1.12	0.16

The waste heat boiler must be considered on its merits and not as an alternative method of heat recovery. As already stated, return of heat to the furnace by regenerators and recuperators is governed by the needs of the furnace. If the thermal conditions in the furnace do not require that the air and gas be pre-heated, installing regenerators may not be justified; when there is adequate demand for steam, a waste heat boiler should be preferred.

On the other hand, when regenerators are installed, there may be sufficient heat left in the gases to justify installing a waste heat boiler as well. Furthermore, in certain cases the ratios between air, fuel and waste gases may be such that the temperature of the outlet gases is too close to that of the water in the boiler to make a waste heat boiler an economic proposition, as shown from the above calculations. This applies particularly in coke oven gas as a flue heating fuel.

In planning new installations, the relative advantages of waste heat steam and steam generated in ordinary boilers should be considered from the point of view of fuel economy. The fuel-saving effect of a waste heat boiler is sometimes expressed as a percentage of the fuel charged to producers used for supplying a furnace.

This is unsatisfactory because the cost of producer coal differs considerably from that of, say, boiler slack, and the *monetary saving* will be less than the saving in *coal quantity* might indicate. There are other costs to be taken into account, both on the waste heat boiler and on the fuel-fired boiler, including that of the fan used with the waste heat installation.

All relevant factors can be taken into account by determining as accurately as possible the average steam output from a boiler and then ascertaining all costs—power, cleaning, maintenance, repair and inspection, capital costs and depreciation. These must be set against the cost of generating this amount of steam in the fuel-fired boilers.

SELECTION OF BOILER

It is very difficult to draw sharp lines limiting the purposes for which each type of waste heat boiler is best suited. According to Gregson¹ these are approximately as follows:

(a) Water-tube designs for handling large volumes of high temperature gases,

particularly where high steam pressures are required with stand-by fuel-firing. These designs are not so successful where a heavy furnace draught is superposed on the circuit, owing to potential inleakage, unless high-grade steel casings are adopted, and if gas explosions are likely to occur in the boiler setting—for example, on the change-over of the reversing valves of the regenerators of an open hearth furnace—the brick set boiler is not suitable.

- (b) Fire-tube designs cover a high percentage of waste heat recovery in the steel, gas, and chemical industries in Britain, as well as for furnaces demanding the handling of medium volumes of medium-to-low temperature gases with considerable suction or—in water gas plants—considerable pressure. The fire-tube design positively avoids inleakage and, in consequence, all troubles therefrom. The use of fusion-welded construction has allowed such boilers to be built for pressures of the order of 450 lb./sq. in.
- (c) Thimble-tube designs—essentially compact vertical units very well suited for internal combustion exhaust gases.

The waste-heat type of boiler is more suitable than other designs for dealing with the gases from refuse destructors, incinerators and from the burning of low grade fuels, where high furnace temperatures are not available.

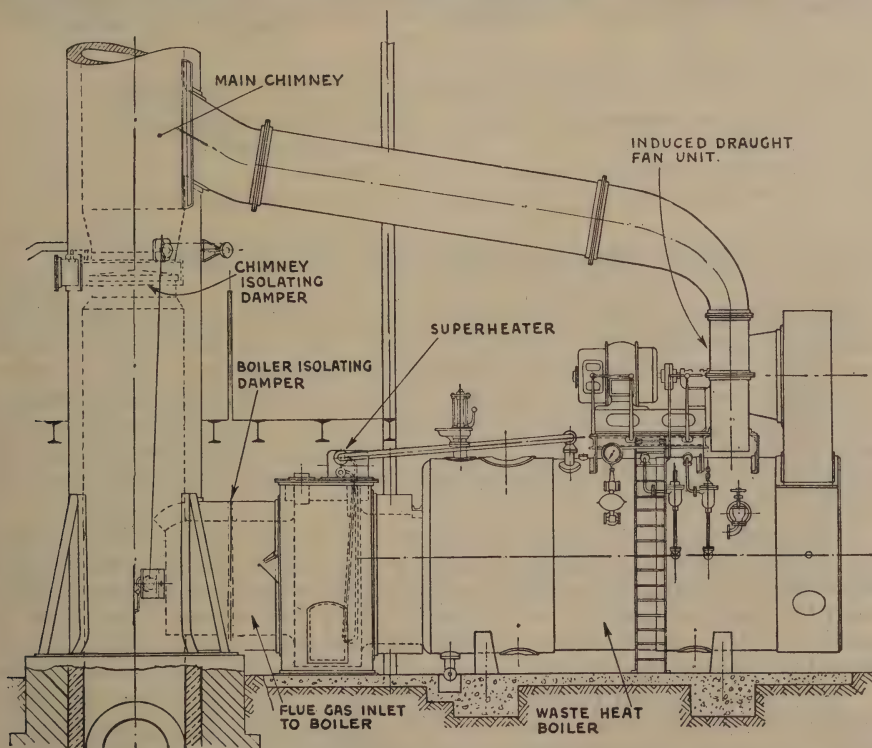


FIG. 3. Application of Waste Heat Boiler to an Open Hearth Steel Furnace.

Figs. 3 and 4 show two examples of the use of waste-heat boilers in industrial practice. (These are reproduced by permission of Messrs. Spencer-Bonecourt-Clarkson Ltd.)

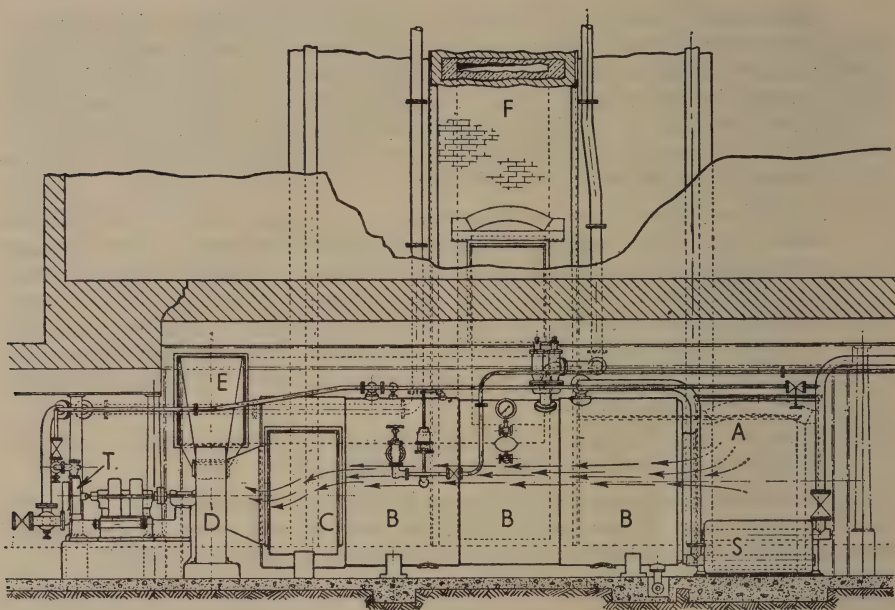


FIG. 4. Application of Waste Heat Boiler in Gasworks Practice.

- | | |
|-------------------------------------|-----------------------------|
| A. Waste flue gases from retort. | E. Discharge duct from fan. |
| B. Waste heat boilers. | F. Retort bench chimney. |
| C. Gas outlet chamber from boilers. | S. Superheater. |
| D. Induced draught fan. | T. Turbine driving fan. |

WASTE HEAT RECOVERY AND THE GAS TURBINE

Although the gas turbine does not come entirely within the orbit of this chapter, its use for waste heat recovery falls within the same category as the waste heat boiler because it either replaces the latter or more generally offers, in conjunction with appropriate boiler plant, a combination unit supplying both power and process steam. It is really more correct to describe such a machine as an air turbine, as it operates on hot air, heated after it leaves the compressor by means of an appropriate air heater arranged in the waste gas flow⁴.

In the sizes involved in typical waste heat recovery practice the air turbine shows considerable advantage over the steam turbine as in these sizes it is more efficient and, when coupled with further waste heat recovery, either from the gases leaving the air pre-heater or by the exhaust gases from the turbine, or by a combination of both, the total heat recovery figure is high. Any type of air turbine appears to be operationally suited to this class of work.

The pioneer plant in Britain, that at Coventry, will operate on the closed cycle system, the exhaust gases from the turbine being used to pre-heat the air flow before it enters the main heat interchanger, the waste gas leaving the main air heater being utilized for steam generation on an installation of continuous vertical retorts using 36 tons of producer coke per day for firing the settings.

The general circuit of the installation is shown⁴ in Fig. 5.

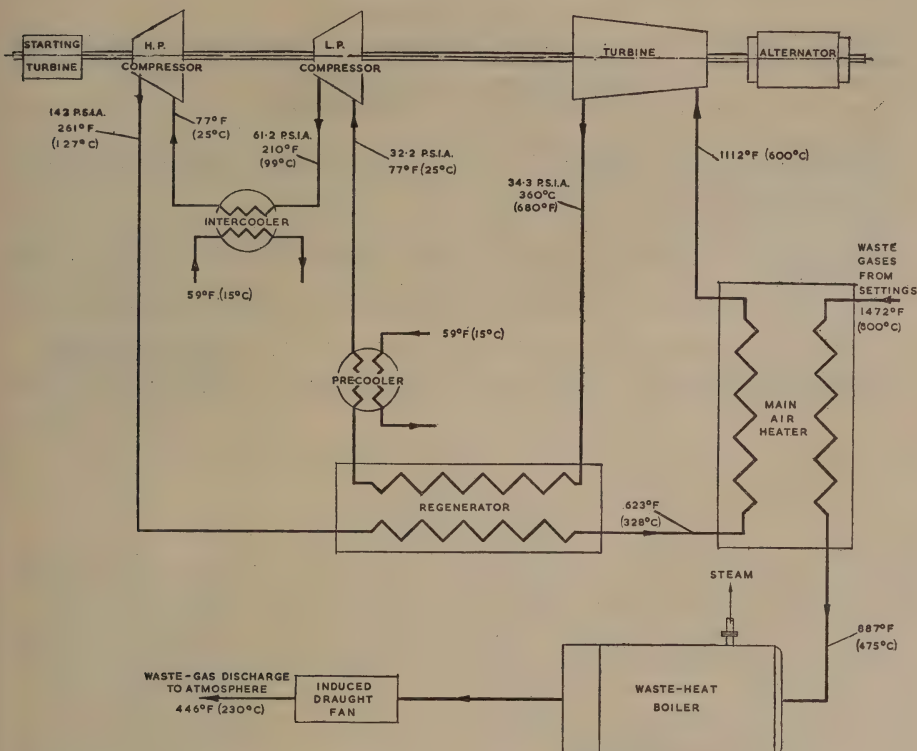


FIG. 5. Waste heat recovery in a closed cycle gas turbine system.

The air turbine will generate about 700 kW. and the heat extracted from the gases after they have left the main heat interchanger will give 5,300 lb. of steam per hour at 120 lb./sq. in. superheated 100° F. Higher electrical yield can be obtained by greater air heater surface at the expense of process steam.

INTERNAL COMBUSTION ENGINES

The exhaust gases from I.C. engines of all types, together with gas turbines, offer attractive possibilities where steam or even hot water can be utilised for, say, process or heating purposes, or indeed in some cases for additive power generation. In very general figures the four-stroke engine offers approximately 1.2 lb. of steam from and at 212° F. per B.H.P./hr. at full load and two-stroke engine approximately 1.7 lb. Fire tube and thimble tube designs are in common use especially aboard diesel-driven ships, and the forced circulation water tube boiler in robust casings has found similar application.

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- ⁴ GREGSON, W., "Fuel Economy and Steam Generation in Marine Practice." (Pres. Address.) *J. Inst. Mech. Engrs.*, 1949, **160**, 52.

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CHAPTER 22

ELECTRIC FURNACES

ELECTRIC furnaces and ovens develop their heat in one of the following ways: (a) by currents applied to or induced within the charge itself, (b) by currents applied to an external resistor, from which the heat is transmitted to the charge either by conduction through a liquid or by radiation and convection through a gas, (c) by the heat may be generated in an arc, one electrode of which may be the charge itself. The various types of furnace may be classed¹ as:

- Induction- and dielectric-heating furnaces ;
- Resistor furnaces;
- Arc furnaces.

The amount of heat, H, developed in a circuit is given by Joule's Law as follows:

$$\begin{aligned} H &= \frac{I^2RT}{1,000} \text{ kWh.} \\ &= 0.86 I^2RT \text{ kg. cal.} \\ &= 3.412 I^2RT \text{ B.t.u.,} \end{aligned}$$

where I is the current in amperes R the resistance of the circuit in ohms and T the time, in hours, for which the current flows. From the above relation the minimum amount of electrical energy required for any heating process can be calculated, and the thermal efficiency of processing equipment estimated.

Economical use of electric furnace equipment demands attention not only to the design, maintenance and use of the furnaces themselves, but also to the economics of the use of the supply. Economical use of the supply is achieved first by arranging that the demand for heat and consequently for electrical energy is maintained as uniform as possible, and secondly by arranging that the power factor of the load is maintained as high as possible.

The *power factor* of the load is the ratio between the "watt component" of the current, in phase with the voltage, and the total current. The latter contains a 90° lagging "watt-less" component required for magnetization at the circuit inductance. This component of the current can be catered for more economically by local installation of power factor correcting capacitors than by demanding it from the supply system.

INDUCTION AND DIELECTRIC HEATING

If a metal is placed in an alternating magnetic field the metal is heated by the currents induced in it.

It is a characteristic of induction heating that the current is not carried over the whole cross-section of the conductor, but tends to concentrate on the surface. This is known as "skin effect," and the higher the frequency the greater is the tendency for the current to remain near the surface. Steinmetz has developed the equation :

$$P = \frac{5,030}{\sqrt{F\mu}} \sqrt{r}$$

where P is the depth in centimetres to which the resulting current penetrates when magnetic flux is induced from the primary:

r is the resistivity of the charge; ohms/sq. cm./cm.

F is the frequency in cycles per second,

and μ the magnetic permeability of the charge (which for iron at higher temperatures is unity).

Thus, for a given material, if the frequency is increased from 50 cycles per second to 2,500 cycles per second, the depth of penetration is decreased to approximately one-seventh.

The resistance offered to a current is inversely proportional to the cross-section of the current path. Therefore, if the depth of penetration is less, the resistance offered to the flow of current is higher. But according to Joule's Law the amount of heat developed is proportional to the resistance, therefore by increasing the frequency the amount of heat developed is also increased for a given current and true cross-section of conductor (the charge).

Heating by induction may be selected as the most economic or convenient method depending upon the size and nature of the charge and the heat-treatment required.²

Non-metals such as wood, rubber, plastics, etc., may be heated in an alternating electric field; in this case the energy results from dielectric losses within the material. The body to be heated is placed between a pair of metal plates to which a high frequency voltage is applied. If the body is homogeneous and of uniform section it will be heated uniformly throughout; since almost all dielectrics are bad conductors of heat this method is particularly suitable for through-heating of thick sections of these materials.

LOW-FREQUENCY INDUCTION FURNACES

A low-frequency furnace may be regarded as a transformer in which the molten metal forms a short-circuited secondary winding, and is designed so as to give the best electrical coupling consistent with easy handling of the charge (Fig. 1.) Two well-known types are the Kjellin and the Ajax-Wyatt. In the Kjellin furnace the bath of metal forms a horizontal annulus around a

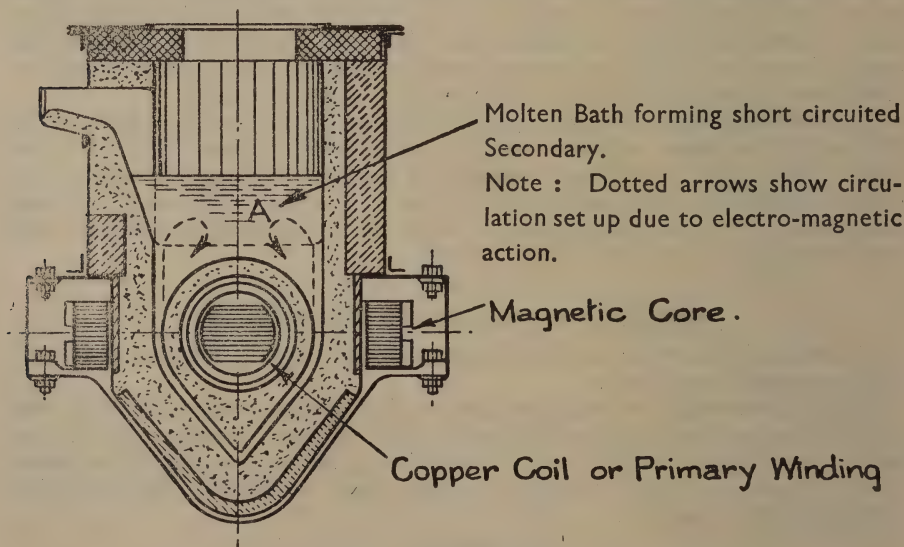


FIG. 1. Section through normal frequency induction furnace.

vertical leg of the transformer on which the primary coil is wound. Furnaces of this type have been built to handle 10-ton charges. In the Ajax-Wyatt furnace, the core carrying the primary coil is horizontal, and is surrounded by vertical channels joined at the bottom and leading up to the bath proper. The molten metal circulates through these channels. The power input necessary

is approximately 50 per cent. above that necessary to melt the charge, the loss being due mainly to radiation.

Since 1940 the use of the low-frequency induction furnace has been extended to the melting of aluminium and its alloys.^{3, 4}

Capacities range from 450 to 6,000 lbs. at ratings of 20 to 500 Kw respectively, the larger furnaces melting up to 2,500 lbs. of aluminium per hour. The power consumption is reported to be 450–500 kWh per ton of metal melted.

The low-frequency furnace was first developed for melting iron and steel and it is still used for deoxidation and refining or where melts of carefully controlled composition are required. A large number are in use in this country for the melting of brass where the close temperature control enables zinc loss by volatilization to be kept to a minimum. These furnaces handle charges of up to one ton. The induction melting of aluminium^{5, 6} is reported to result in a reduction in hydrogen absorption and of other impurities, particularly oxide inclusions and sulphur. The Ajax-Wyatt furnace was also used in Germany for melting zinc and for the semi-continuous casting of brass.

The low-frequency induction furnace has a practically steady load throughout the melting period, which is normally one hour. The large air gap between the primary coil and the charge or short-circuited secondary makes the power factor of the unit low, and where the supply is at mains frequency, or higher, power factor correction must be applied.

The furnaces are by nature single-phase or two-phase; thus to operate them with reasonable balance on a three-phase supply specially wound (Scott-connected) transformers are used, to which the smaller furnaces are connected in pairs and the larger singly. (See Fig. 2.) Three-phase units with three windings and four conducting channels have been used in Germany.

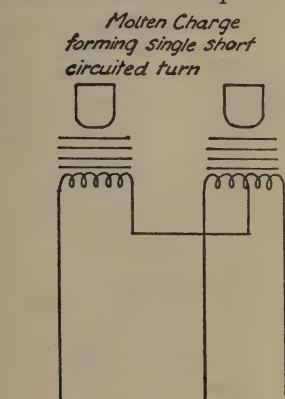


FIG. 2. Electrical diagram for 2-phase normal frequency operating from 3-phase supply.

HIGH-FREQUENCY FURNACES

There appear to be no accepted limits to the frequency ranges described as low, medium, and high-frequency. In this section the term "high-frequency" is taken to imply frequencies above 500 c./s., although the present tendency is to regard low-frequency as being 50–1,000 c./s., medium frequency 3,000–30,000 c./s. and high frequency 100 k.c.s. or above.

(a) Induction Heating

A high-frequency furnace (see Figs. 3 and 4) must be designed so that the heating coil, which consists of a water-cooled copper tube, is placed as close to the charge as possible, since the field strength and the coupling fall away rapidly when distant from the coil. An important characteristic of this type of heating is that the current is flowing in a thin surface layer and causes the surface heating effect. The higher the frequency the shallower is the depth of skin within which heat is generated.

Two main considerations govern the choice of frequency—(a) the total power required and (b) the type (i.e. penetration) of heating. The total power required may decide whether a machine or a valve-oscillator set is to be preferred; if a generator is selected the frequency is necessarily limited to 10,000 c./s. Valve sets having output powers of 1–50 kW. are widely used. Larger sets have been built but the largest set in Britain is rated at 250 kW.

For higher outputs generator sets are necessary. In the lower output range where either a motor alternator or a valve generator might be considered practicable, it is accepted that the valve generator is the cheaper.

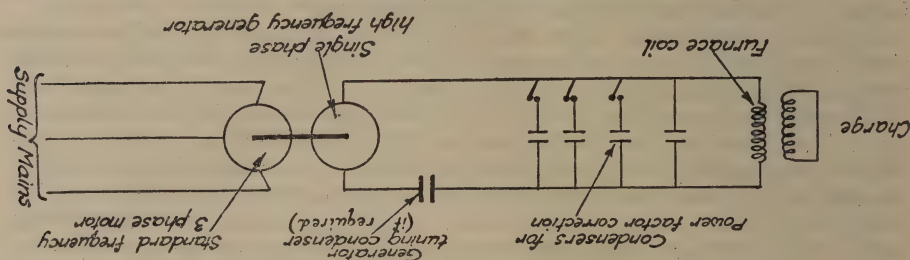


FIG. 3. Electrical diagram for high frequency induction furnace.

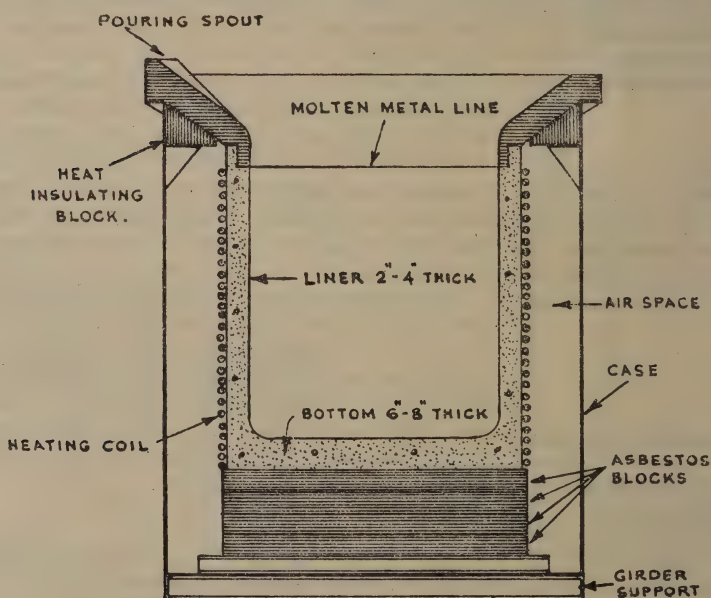


FIG. 4. Section through high frequency induction furnace.

In furnaces for melting, the frequency is determined by the total power required and must be large enough to ensure maximum heating efficiency on a charge of given diameter. Because of the frequency used (1,200–2,500 c./s.), this requires a motor generator set to provide the supply, the motor of which is of the three-phase type, and therefore ensures a balanced load on the supply,

The demand of the furnace has a well-marked trend. Assuming one-hour melting-time, the load falls steadily from 80 per cent. when switched on first, to 50 per cent. in eight minutes. It then rises steadily during the next eight minutes to 100 per cent., and thereafter remains at between 90 and 100 per cent. Throughout the period the power factor is low, and to avoid an excessively large generator, banks of condensers must be brought into circuit, the maximum correction being required during the latter half of the period.

For efficient hardening, the depth of penetration must be small compared with the radius of the charge, and the surface loading of the charge should be high, say, $\frac{1}{2}$ –3 or even 4 kW/sq. cm. Thus, the smaller the piece to be hardened

the higher is the frequency required and therefore the more is a valve oscillator to be preferred to a motor generator. In practice it seems difficult to obtain hardened cases of less than 0.040–0.050 in., using a 10 k.c./s. alternator; cases as shallow as 0.005–0.010 in. may be obtained with a valve oscillator.

High-frequency heating is used for various types of metal heat treatment, e.g. melting, brazing, soldering, hardening, annealing and tempering. In the iron and steel industry it competes with coke-fired crucible furnaces for the production of high-quality steels. Valve-oscillator equipment finds application, particularly in the melting of small quantities of metals (or non-metals when enveloped in a conducting crucible), and in the heating of selected areas or parts of metal bodies. As the effective field is restricted to a shallow region close to the high-frequency coil, coils may be shaped to conform with local areas of metal bodies. In this way soldering or brazing at a point or along a line may be done rapidly.

Although heating or melting by high-frequency usually involves a high capital outlay, the process has attractive features, including a rapid rate of heating, cleanliness, the absence of furnace gases, and adaptability to vacuum treatment. The following figures⁷ for power consumption have been quoted, but it should be noted that these do not necessarily determine the relative economics of the process:

heating steel.. ..	..	600–900 kWh per ton
heating cupro-nickel ..	..	400–600 kWh per ton
through hardening steel ..	..	300–400 kWh per ton, up to 1½ in. diam.
surface hardening steel ..	..	20– 40 kW sec./sq. in. for 1/16 in. case or round bar.

Typical application of valve-oscillator sets are as follows:

- a 1 kW generator “through” hardens 240 diesel engine injection parts per hour.
- a 2 kW generator soft solders the tops of capacitor cans into position at the rate of 700 per hour.
- a 5 kW generator brazes tungsten carbide tips to 5/8 in. square steel shanks in 25 seconds.
- a 25 kW generator produces a hardened skin 0.012 in. deep on a 3/4 in. diam. 0.7 per cent. carbon steel rod in 1½ seconds and a 0.040 in. case in 2 seconds.

One large motor-generator plant rated at 3,300 kW. has been installed in England⁸ for heating billets prior to forging; it utilizes frequencies of 3,000 and 10,000 c./s. to cater for the variation in size of billets. The advantages of the plant include reduction of scale, improved die life, elimination of time-lag in starting up, good working conditions and cleanliness.

A high-frequency melting furnace installation in Wednesfield for the production of steel castings, tool steels and high quality steels consists of three furnaces for handling 10 cwt., 5 cwt., and 3 cwt. per hour respectively. Single-phase current at 2,000/1,000 volts and 1,000 c./s. is supplied from a 400 kW motor generator. Such furnaces afford ready control of the melting temperature and produce clean steels of uniform composition. A furnace installed in the U.S.A. for the melting of copper-base alloys⁹ consists of two high-frequency generator units, rated at 100 kW (150 H.P. motor; 3,000 c./s.), and 175 kW (260 H.P. motor; 960 c.p.s.) respectively. Melting speed varies with the type of charge and with the thermal characteristics of its constituents. The 175 kW unit is rated at 1,000 lb. of brass per hour and will melt a charge of 150 lb. in 15 to 20 minutes at each of two stations, giving a total output of 16/21 lb. per minute. The 100 kW unit is rated at 525 lb. of brass per hour, giving a total capacity of 8–11 lb. per minute.

(b) Dielectric Heating

Dielectric heating enables a uniform temperature to be obtained throughout a poor conductor of heat.

The power loss in a dielectric increases with the square of the voltage. If the loss angle (power factor) of the dielectric remains about the same, the power loss increases linearly with the frequency. The voltage cannot be increased indefinitely, however, otherwise flash-over occurs, so that frequencies greater than 1 megacycle per second are usually chosen in order to obtain a reasonable rate of heating. There is also an upper limit to the frequency, which may be set either by the equipment design or by the dimensions of the charge treated; for most applications it lies within the range 10–80 Mc./sec. The valve generator is of the same type as that used for high frequency induction heating.

For any specific treatment the first requirement is to determine the power necessary to achieve a sufficiently high rate of heating, this being dependent upon thermal considerations. If necessary, an air-gap may be introduced between the electrodes and the article to be treated. This necessitates a high voltage across the electrodes and increases the risk of "flash-over"; the air gap is therefore limited as much as possible.

Dielectric heating is being used for the processing of thermo-plastics, the preheating of thermo-setting plastics and wood gluing.^{10,11} The heating times are remarkably short in these treatments; about $\frac{3}{4}$ lb. of plastic may be pre-heated per minute for each kilowatt put into the charge; 4 lb. rubber pre-forms $1\frac{1}{2}$ in. thick require only 15 minutes in the press after being pre-heated by high-frequency; a 5 kW. generator will set up to 600 sq. in. of glue line in 30 seconds; in a synthetic sponge process the drying time was reduced from, 70 hours to a few minutes.

ARC FURNACES

In 1947 there were in Britain 185 electric steel-melting furnaces of capacities up to 35 tons, mainly of the arc type.¹²

In arc furnaces (Figs. 5 and 6) the heat is generated either by an arc formed between two electrodes (*indirect arc*) or by an arc formed between the

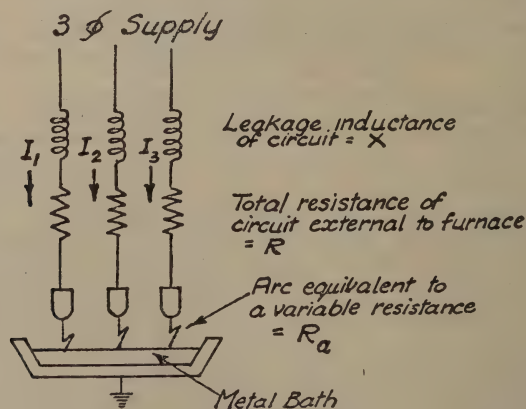


FIG. 5. Equivalent circuit for 3-phase arc furnace.

electrodes and the metal charge (*direct arc*). In the former case the heat reaches the charge mainly by direct radiation and wall reflection, whereas in the latter case some additional heat is generated by the passage of the electric current through the metal, but the amount is negligible in relation to the total heat generated by the arc.

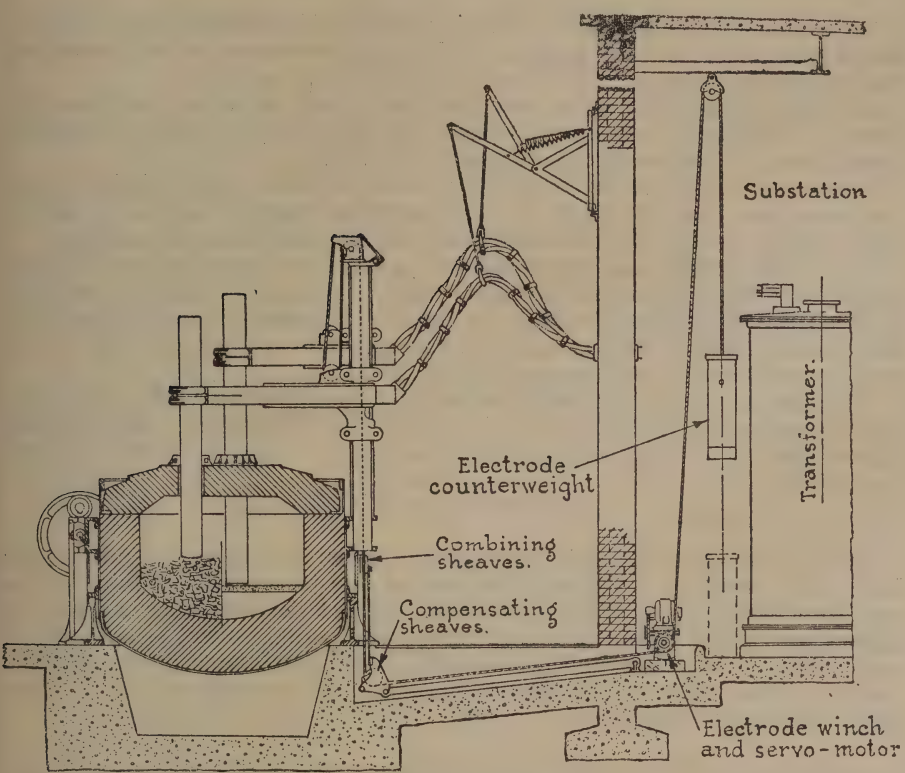


FIG. 6. Arc furnace.

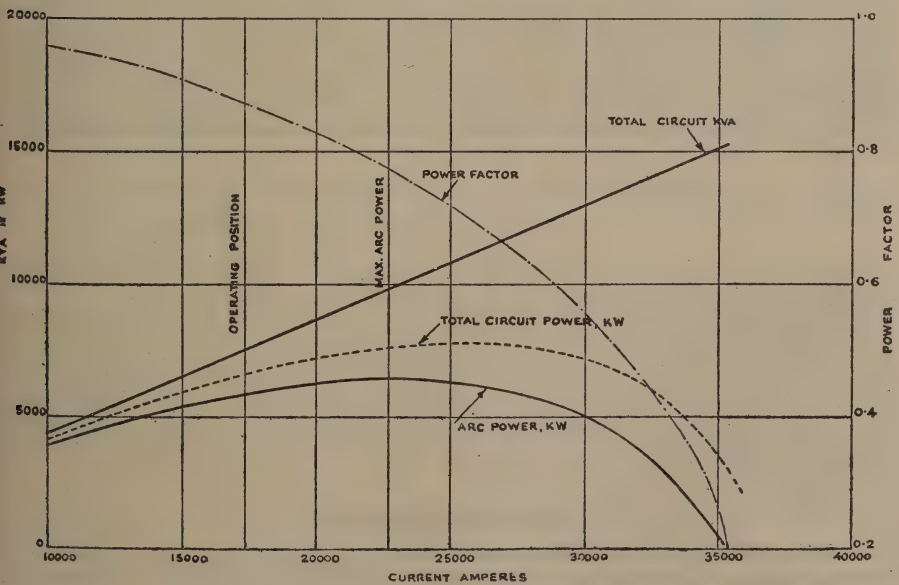


FIG. 7. Characteristic curve of arc furnace.

To achieve stable operation, a certain amount of inductance must be introduced into the circuit, and the value of this inductance more or less determines the maximum power which can be developed by the arc.

In practice the power factor resulting from operating under maximum arc power conditions is poor and therefore it is customary to run at somewhat lower power to improve the power factor (Fig. 7).

The *arc radiation furnace* consists of a refractory-lined steel cylinder having two electrodes entering along the axis and it is usually designed so that it may rock or rotate, thus increasing the rate and uniformity of heating.

Non-ferrous metals and alloys, and iron, are melted in furnaces of this type which have the following advantages: rapid heating rate; accurate temperature control; reasonable gas-tightness; quick replacement of the furnace body if a different type of melt is required. The melting capacity of a unit of this type is usually within the range of 40 to 3,000 lb.

The direct arc furnace normally consists of a lined chamber with a removable roof through which the two carbon electrodes enter, the height of the electrodes above the bath being automatically controlled throughout the melting operation.

Load Characteristics

Until a pool of metal exists in the charge, when a steady arc can burn, the load of arc furnaces is violently fluctuating due to repeated striking of the arc. In addition, the charge will often fall against the electrodes and cause a short circuit. These conditions may occupy any period up to $1\frac{1}{2}$ hours during each cycle of operations, and the variation in load may be from zero to three times nominal full load, the changes occurring continuously on one or other phase throughout the period (Fig. 8).

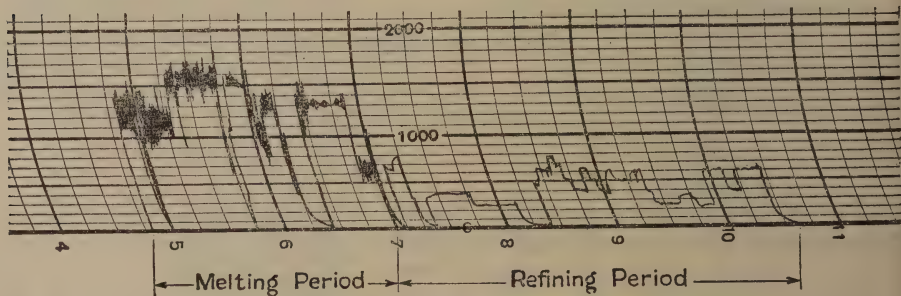


FIG. 8. Chart of current consumption in an arc furnace.

For the last third of the melting time conditions will be relatively stable and the load will approximate to 85 per cent. of nominal full load.

Where refining is subsequently done, the arc voltage is reduced, usually in several stages, and during each stage conditions are fairly steady. The refining period varies widely and depends mainly on the initial quality of the charge and the degree of accuracy required in the final material analysis. The load is now roughly from one-quarter full at the start to one-tenth full at the end of the refining time, which may be as long as five hours but usually does not exceed $2\frac{1}{2}$ hours.

RESISTOR FURNACES

In industrial furnaces having solid resistors (Fig. 9) the composition of the heating element depends largely upon the maximum working temperature, and is generally as follows:

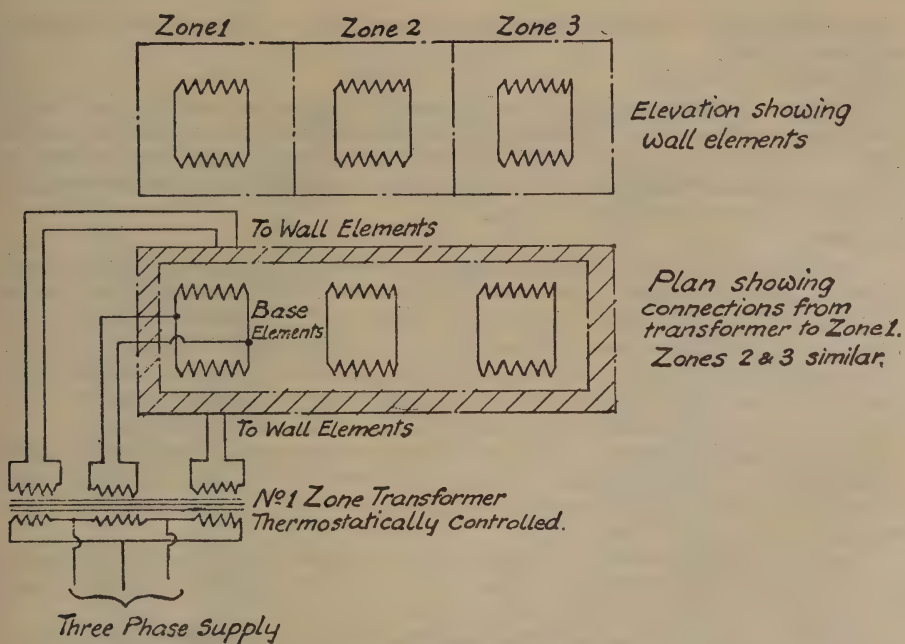


FIG. 9. Electrical diagram for 3-zone resistance furnace with "on-off" thermostatic control.

- Up to 1,000° C., 65/15/20 Ni/Cr/Fe.
- Up to 1,150° C., 80/20 Ni/Cr.
- Up to 1,350° C., Cr/Fe/Al (Kanthal) or Silicon carbide.
- Above 1,400° C., Carbon.

Most commercial resistor furnaces are built to operate at temperature below 1,200° C.

Furnaces are in operation using molten glass as the resistor for temperatures of 1,000° C. to 1,500° C. The glass is contained in channels on each side of the hearth and current is carried to the bath by carbon electrodes immersed in the glass. Such furnaces may be of the batch or continuous types and have been used for the heating of billets, prior to forging and rolling.¹⁵

When used for melting, the resistor furnace has a perfectly steady good power factor load, lasting for about one hour per charge.

When used for heat treatment, the electrical load depends on several factors, e.g. method of control, method of charging and duty.

(a) Method of Control

The cheapest and commonest form of temperature (and thus electricity) control is the so-called "On-Off." When this is used, after the furnace and charge have been brought up to temperature the supply is switched off until a pyrometer registers a pre-determined permissible drop when the supply is again switched on and left on until the maximum allowable temperature has again been reached. This sequence is repeated throughout the treatment cycle.

Alternatively, when the furnace and charge have reached the correct temperature, the supply is reduced so that the heat input as nearly as possible balances the furnace losses, and only rarely is the full load again switched on. A variation of this method is to provide an induction regulator which varies the applied voltage smoothly and in accordance with the furnace demands. Although expensive in first cost, this latter form of control has the advantage

of not subjecting either the resistance elements or the supply system to sudden changes in load.

(b) Method of Charging

In batch charging, each group of articles is treated separately; the charge has thus each time to be brought up to required temperature when the process on the previous charge is finished. In continuous charging, the fresh charge is fed in continuously and at a uniform rate; thus the load is more nearly constant as cold charge succeeds cold charge.

(c) Duty

The numerous types of heat treatment for which electric furnaces are used differ in the temperatures and times they require. The five usual treatments are: hardening, annealing, tempering, normalizing, and case hardening. To these must be added solution and ageing for aluminium and "electron" metals. The temperatures and times vary between 1,350° C., for five minutes, for hardening tool steels to 180° C., for two hours, for tempering ordinary steel, and include a steady temperature of 500° C. for 96 hours for nitriding.

In the ceramic industry there are three treatments for earthenware and china: biscuit firing for about 72 hours at 1,200–1,400° C., gloss firing for 24 hours at 1,150° C., and decoration firing, when painted, for 15 hours at 700–900° C.

Finally, steatite treating is a single-pass continuous process lasting 24 hours, and comprising three zones of temperature: 0–1,000° C., 1,000–1,400° C., and 1,400–700° C.

It is clear therefore that with this variety of conditions to be met no accurate generalizations can be made regarding the electrical load on a resistor furnace.

OTHER TYPES OF FURNACES

BATCH FURNACES

A very wide variety of batch type furnaces is in use at present, ranging from low temperature convection ovens to the high temperature furnaces used for annealing and hardening. Such furnaces consist of a heated insulated container into which the charge is fed. For convenience they may be classified in two types, namely, (a) vertical and (b) horizontal.

Some of these furnaces of simple design are made for the heat treatment of material in air, but many of them are designed for use with special furnace atmospheres. In this latter case precautions must be taken to ensure that the required atmosphere composition is maintained within the furnace chamber and hence furnaces of this type often incorporate special features of design to ensure gas tightness.

- (a) Popular forms of vertical batch furnaces are the pit type (Fig. 10) and the bell-base type (Fig. 11). These are fully described in connection with controlled atmosphere furnaces (see below), but with obvious simplification may be used without such control.
- (b) Horizontal furnaces range from the small batch types in which the material is charged into the heating chamber by hand, to the larger units where special charging methods are used. The latter may include a charging machine on which material for treatment is stacked upon metal arms which carry the charge into the furnace, lower it upon the hearth and then retract. (Fig. 12). Alternatively, the charge may be stacked upon a bogie hearth which is then moved into the furnace and forms the base of the heating chamber. When necessary, both of these furnaces may be provided with seals to permit of their use with special atmospheres or, alternatively, work can be enclosed in a heat-resisting container into which a special atmosphere is fed.

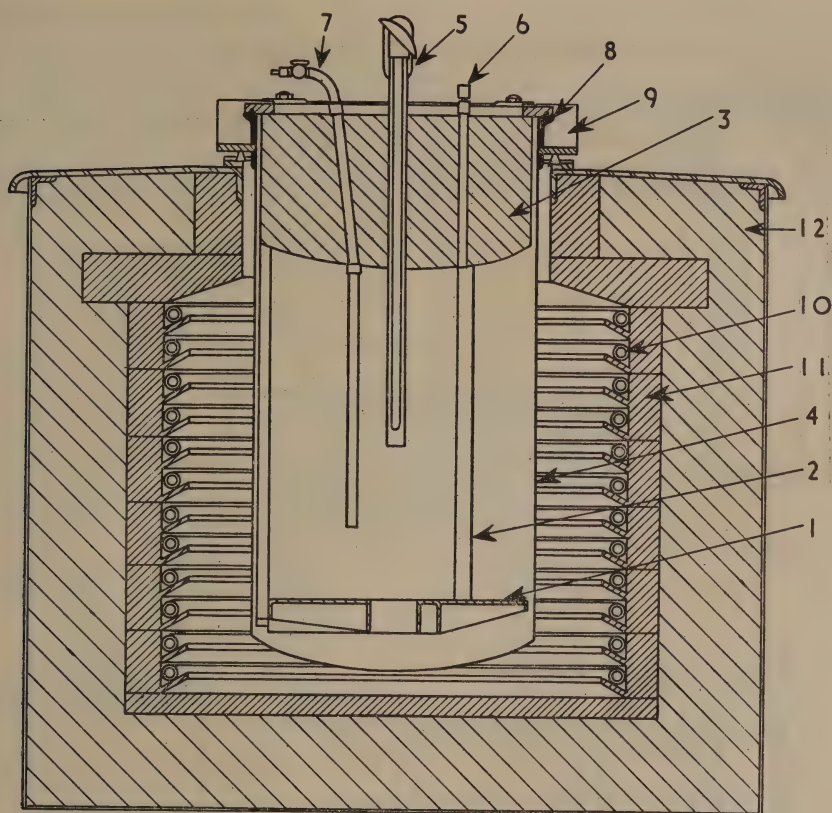


FIG. 10. Vertical pit-type furnace.

- | | |
|------------------------------------|-------------------------|
| 1. Base casting. | 7. Gas inlet. |
| 2. Heat-resisting suspension bars. | 8. Rubber ring seal. |
| 3. Thermally-insulated pot-head. | 9. Water trough. |
| 4. Cylindrical annealing pot. | 10. Heating elements. |
| 5. Pyrometer. | 11. Refractory lining. |
| 6. Non-return valve or gas outlet. | 12. Thermal insulation. |

Furnaces of the above types are used without any special sealing devices for the heat treatment of material not appreciably oxidized by air (e.g. aluminium alloys) or where some degree of scaling is permissible, e.g. the annealing of castings, forgings, bar stock, etc. For certain applications, especially at temperatures below 600°C ., fans may be incorporated in the design in order to improve the rate of heating and the uniformity of temperature¹⁶ (Fig. 13).

The rocking resistor furnace¹⁷ consists of a refractory-lined cylindrical steel shell mounted on four rollers with its long axis horizontal and having a central doorway for charging. A carbon element is held (along the furnace axis) by carbon blocks at each end; these are screwed on to water-cooled holders. The furnace is used for the refining and super-heating of cast irons and for steel or non-ferrous metal melting. The heating is not so intense locally as in the arc furnace. During heating the furnace may be rocked through 120° , thus increasing the heating rate. Power consumption is 150–180 kWh. on a single phase at a current of up to 5,000 amp., supplied from a tap-change transformer; the average energy consumption for each ton of iron melted is 900 to 950 kWh. Usually the furnace has a capacity of 600 lb. to 1,200 lb. of molten cast iron and is operated at temperatures up to $1,550^{\circ}\text{C}$.

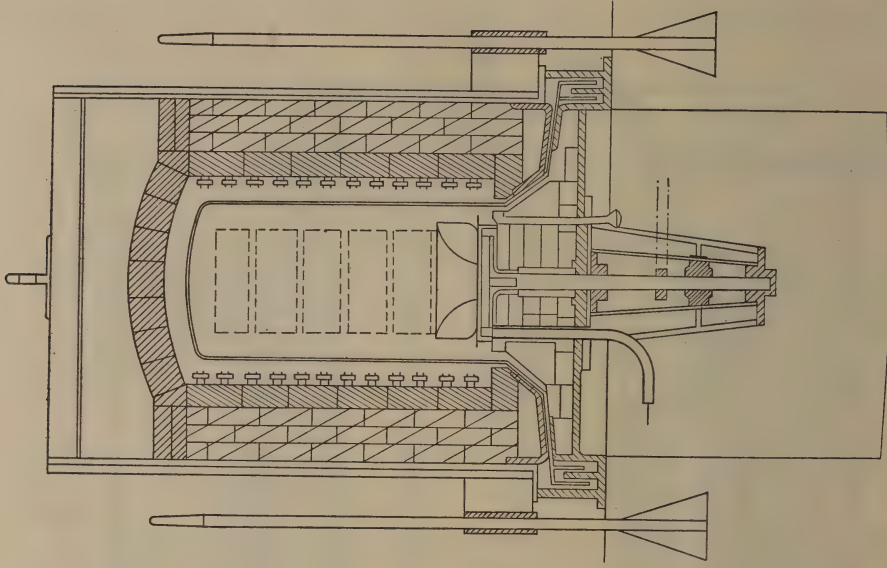


FIG. 11. Bell-base furnace (base).

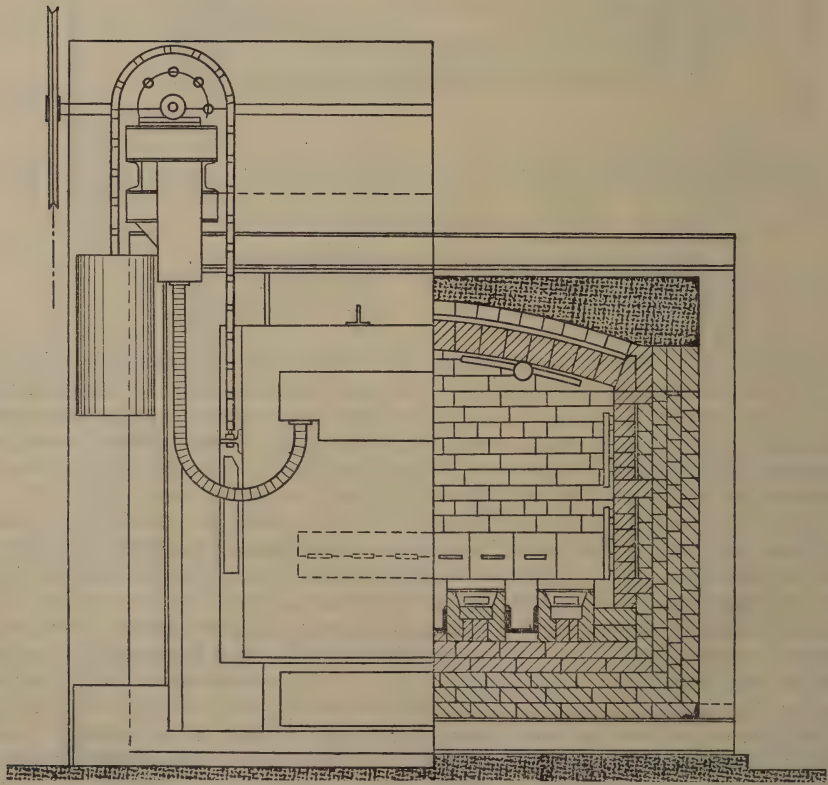


FIG. 12. Horizontal batch type furnace with charging machine.

CONTINUOUS FURNACES

Many continuous furnaces are in use for the treatment of charges in air, but they may be readily adapted for treatment in a controlled atmosphere. The rotary hearth furnace (Fig. 14) has an annular hearth carrying the charge which is exposed to radiation from the sides. The charge is loaded and unloaded through doors close together on the periphery of the hearth. These furnaces may be used for the decoration or firing of pottery at temperatures up to $1,150^{\circ}\text{C}$.

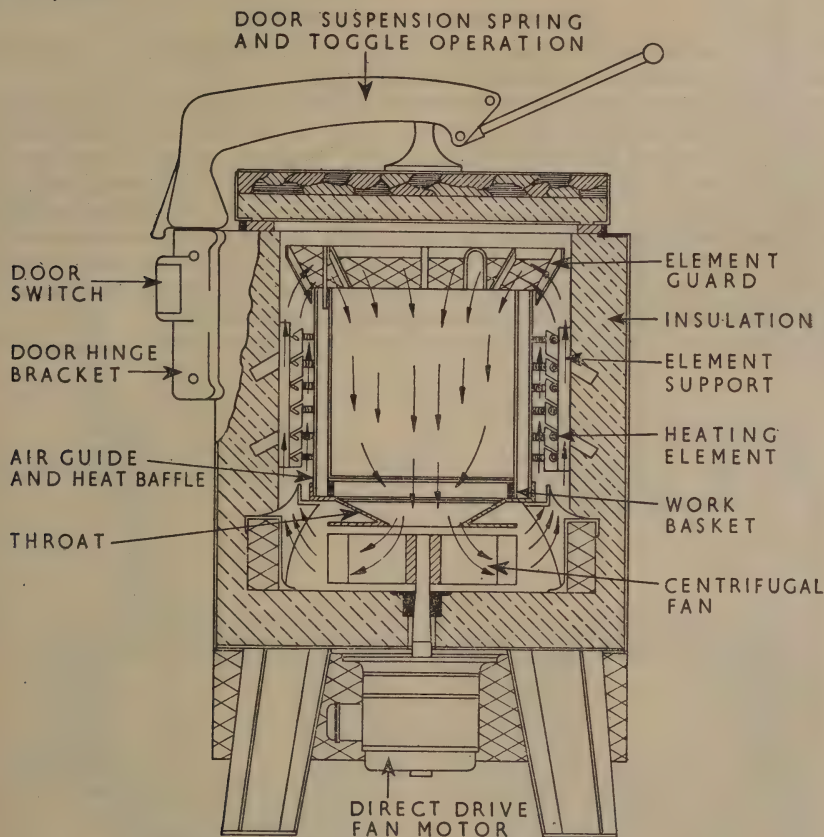


Fig. 13. Vertical forced air circulation furnace.

The *mesh belt furnace* has an endless conveyor of woven heat resisting wire travelling through the furnace and back to the charging end. For heavier loads a *chain belt furnace* may be employed, in which the conveyor is constructed of heat-resisting links pinned together. The *pusher-tray furnace* contains skid or rollers over which trays containing the charge are pushed, the trays forming a continuous line through the furnace and being pushed by gear at the charging end. The *driven roller hearth furnace* (Fig. 15) carries the charge on driven rollers suitably spaced through the length of the furnace, the material being fed directly on to the rollers. Where material may be handled in strand form (such as wire or strip), it may be fed throughout the furnace from uncoiling gear at the loading end on to coiling gear at the discharge end without being supported during its travel through the furnace. These furnaces may be vertical or horizontal.

In one type of furnace¹⁸ aluminium sheets are treated continuously on a rope conveyor. The loading and unloading conveyors have non-metallic ropes which are interlaced with the furnace conveyor. Heating is by hot air circulation, the air being passed over heaters remote from the furnace chamber and then deflected over the work; it is claimed that this design enables the sheet to be raised to the annealing temperature in two or three minutes and gives close control over the heat treatment.

CONTROLLED ATMOSPHERES

Much of the finished metal used to-day is heat-treated in a controlled atmosphere at some stage during manufacture.

Controlled atmospheres were first developed for the protection of the surface finish of a metal during a heat treatment such as annealing. As some metals oxidise readily when heated in air, reducing atmospheres were developed in which the charge could be heated without surface oxidation occurring. The reducing power of an atmosphere must be increased for metals that are more readily oxidized; thus silver may be annealed in air, copper in steam or carbon dioxide, mild steel in gases containing hydrogen or carbon monoxide and stainless steel in very dry hydrogen. These four atmospheres are representative of the types of atmosphere in which annealing is carried out.

Additional more recent applications have come with the development of

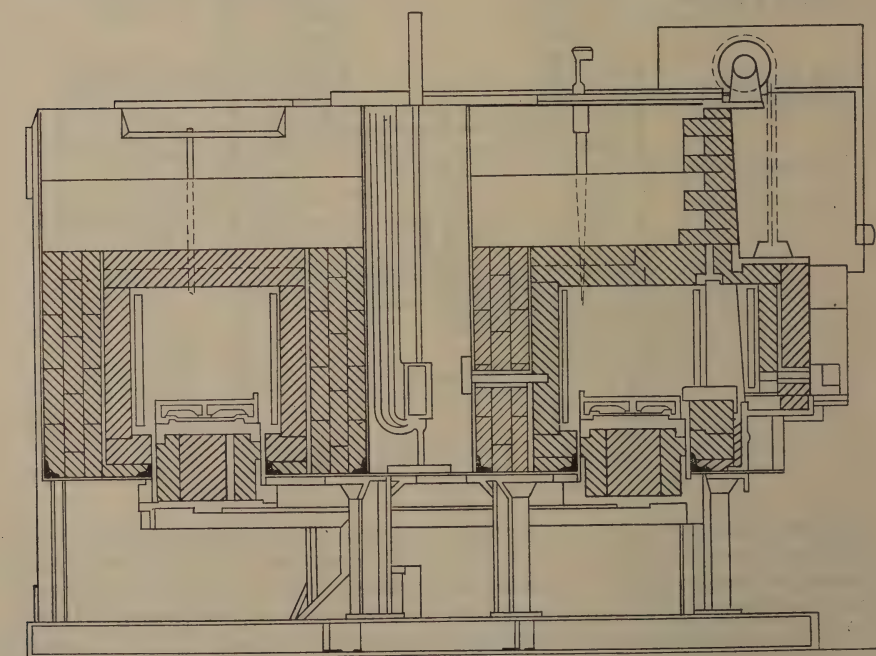


FIG. 14. Rotary hearth furnace.

powder metallurgy techniques to present chemical actions by the atmosphere during the process of sintering. The use of molybdenum as a resistance element necessitates the use of hydrogen for protecting the resistance element as well as the work.

There are in general three types of batch furnaces, viz.: sealed pot, bell type and the elevator type (Fig. 16).

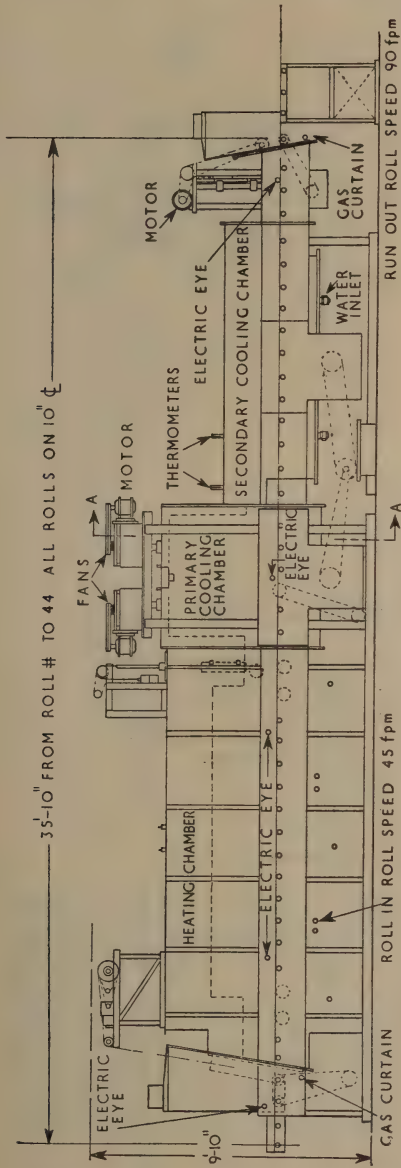


Fig. 15. Driven roller hearth furnace.

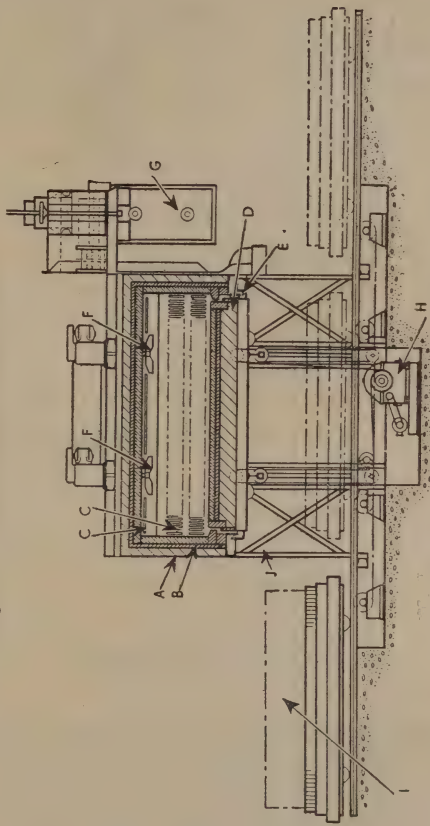


Fig. 16. Elevator type electric furnace.

There are many other applications for controlled atmospheres in the variety of heat treatment processes carried out to-day. For a more detailed treatment of this subject the reader is referred to the published literature.^{19, 20}

Processes in which the entire heat-treatment cycle is carried out in a batch furnace with controlled atmosphere include the following: nitriding of special steels (at about 500° C. in ammonia), annealing of silicon-steel (at 1,150° C. in dry hydrogen), annealing of brass and nickel-silver; "blueing" of silicon-steel and mild steel in steam or burnt town gas; sintering.

Fig. 17 illustrates a type of batch furnace in use for gas-carburizing. A popular type of furnace for gas-carburizing is rather similar in design to that

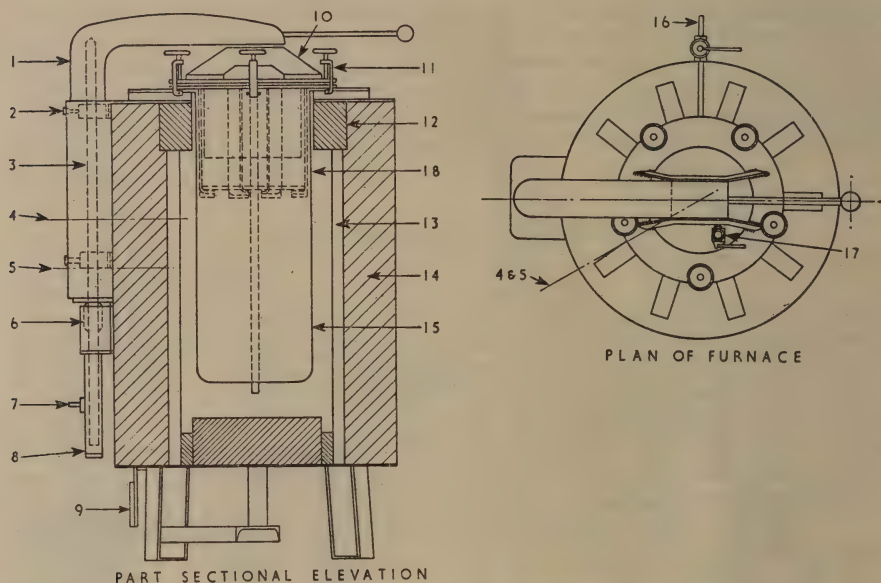


FIG. 17. Vertical batch furnace, for gas carburizing.

- | | |
|-------------------------------------|---------------------------------|
| 1. Door support arm. | 10. Retort door support. |
| 2. Ram bearing. | 11. Retort door clamp. |
| 3. Ram. | 12. Vestibule. |
| 4. Thermocouple. | 13. Heater bricks and elements. |
| 5. Thermal fuse. | 14. Furnace brickwork. |
| 6. Ram packing. | 15. Retort. |
| 7. Cylinder inlet-port. | 16. Gas inlet. |
| 8. Cylinder. (Hydraulic door lift.) | 17. Gas outlet. |
| 9. Terminal board. | 18. Jig support. |

already described for air-tempering. The charge is first loaded into a cylindrical container which is then lowered into a hot cylindrical pit-type furnace having a fan in the base. The furnace cover is then moved into position, making a gas tight-seal. The carburizing atmosphere is then admitted to the charge and the fan started so as to maintain a high speed circulation over the work.

Since 1949 a horizontal batch furnace with gas-tight heat-resisting muffle has been in operation in Britain treating medium carbon steel sheets prior to forming. The furnace, though of simple design, is of interest in that the treatment takes place in an atmosphere which maintains the correct carbon content in the steel during the heating operation.

The reader is again referred to the literature for a more detailed treatment of the subject of controlled furnace atmospheres.

Continuous furnaces are used for controlled atmosphere heat treatment, suitable provision being made for preventing ingress of air into the working chamber and cooling zone where present.

Wire or strip may be treated continuously in a single strand furnace (Fig. 18). The treatment for wire is either a protecting or an annealing operation; nickel-chromium wire requires an atmosphere of cracked ammonia during the annealing treatment in order to preserve a suitable surface finish. Some electrical steel strip is now being decarburized in this country in a continuous strand furnace.

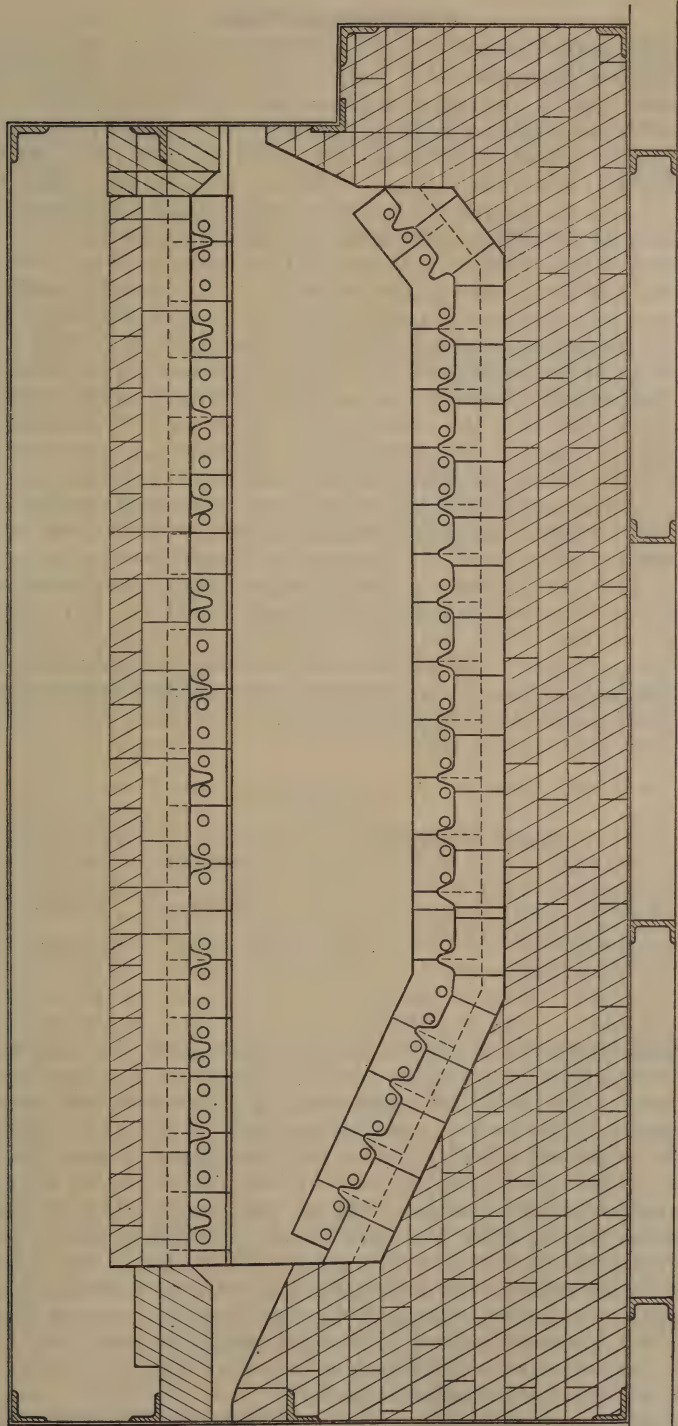


FIG. 18. General arrangement of catenary furnace for strip or wire.

RADIANT HEATING

Since 1936, many developments have taken place in the application of radiant heating methods.^{13, 14, 21} In certain heat treatment, where previously low temperature convection ovens would have been considered suitable, increased efficiency with much shorter heating time may be obtained by using a radiant heating furnace. Where charges are such that heat may be rapidly absorbed by radiation and where the process does not necessarily require the maintenance of a low temperature for long periods, radiant heating may be the most economical and efficient method. (See also Chapter 25.)

The rate of radiation from a source of heat increases rapidly with rise in temperature. Thus, for the same output, a much smaller surface area is required for a high temperature emitter than for a low temperature one, with a consequent reduction in thermal lag and convection loss. (See Chapter 9.) However, since radiations from lower temperature sources are of longer wave-lengths, a dull emitter is sometimes preferred in those cases where the surface of the charge is such that the absorption is higher for long wave-lengths than for short. One of the first types of high temperature radiation source used in industry was the ordinary lighting lamp mounted in a reflector; special lamps, some with internal reflectors, have since been developed, having a filament temperature of 2,500° C., which is somewhat below the filament temperature of the standard lighting lamp. The intensity obtainable from lamp equipment is determined by the closeness of spacing of the lamps; with 250-watt internal reflector lamps the maximum electrical input to a bank is 1,000 watts per sq. ft.

The following figures indicate the rate of heating achieved by a radiant heating furnace, having an input of 840 watts per sq. ft. to two heating banks, compared with natural convection heating:

Material—0.13 in. steel panels.

Method of heating	Time to reach	
	200° C.	240° C.
Radiant	5 mins.	10 mins.
Convection (Air temperature 300° C.)	17 mins.	26 mins.

When high intensities are required nickel-chromium elements mounted in ceramic formers and operating at 900° C. may be used. These must have a much larger area than lamp filaments owing to the lower element temperature; thus it is not possible to focus the radiation on to the work. Alternatively, sheathed-wire element troughs are coming into extensive use. The furnace is designed so as to minimize conduction and convection losses but, like other low temperature sources, the elements and formers have a high thermal lag.

Radiant heating is used for paint stoving, fabric proofing, pre-heating plastics, setting synthetic resin adhesives, and for the drying of latex, gum, printing ink and many other materials. The plants are flexible and yield a large output of work in a comparatively small space. In many instances, as compared with convection ovens, stoving time has been reduced from about an hour to a few minutes only, with resulting economy in labour and floor space, and an increased production rate.

The following are typical examples of radiant heating plants in use for paint stoving:

(a) *Paint Stoving after Electrostatic Spraying*

A conveyor carries motor car wheels successively through electro-static spray booths where two wet-on-wet coats of paint are applied and through a lamp plant for stoving the paint. The equipment handles 360 wheels per hour. The special advantage of radiant heating is that it permits rapid stoving (3 minutes) and gives a short stoving plant for wheels which are necessarily travelling in line with axes vertical (to suit electrostatic spraying).

(b) *Evaporating Surface Moisture and Stoving Paint*

All components of an aluminium car body are processed on a conveyor which carries them through a spray pre-treatment plant, water wash, lamp plant for drying, spray booth in which two wet-on-wet coats of paint are applied and lamp stoving plant.

The drying plant is 20 ft. long, loading 200 kW. and the stoving plant is 32 ft. long, loading 250 kW. The drying and stoving times are $3\frac{1}{2}$ minutes and $5\frac{1}{2}$ minutes respectively and the plant handles 350 sets of components per 40-hour week.

(c) *Stoving Paint and Printing Ink on Collapsible Tubes*

The usual method for finishing tubes is to roller coat with enamel, place in racks on trolleys until 'tack dry', print, replace on trolleys, stove in convection ovens, remove, pack. This necessitates a considerable amount of handling, the trolleys and ovens occupy a large amount of floor space and the risk of damage from dust deposition and other causes is high.

By using open coil elements it is possible to get sufficiently rapid heating rates to enable ovens to be made short enough for inclusion on conveyor lines. For example, enamel drying on collapsible tubes takes about 30 seconds and a 4 ft. long oven will deal with tubes travelling at the normal production rate of 40 per minute. The whole process of enamelling and printing can be completed on a single conveyor line.

SALT BATHS

Salt baths may be heated electrically in three ways. The heat may be generated within the salt by passing current between suitable electrodes dipping into the bath (Fig. 19); such a method is applicable to all salt baths. In the second method the bath is supported within a furnace, and heated by radiation from the resistors. In the third method, which may be used for low-temperature treatments such as annealing aluminium alloys, immersion heaters are inserted into the salt.

Typical applications include the heat treatment of high speed tool steels, stainless and other steels, patenting of steel wire, solution heat treatment and annealing of aluminium-base and copper-base alloys, cleaning of ferrous metals, cyaniding, and carburizing.²² Thus carbon steel in coils can be annealed between draws at 650°/750° C., stainless steels may be annealed at 1,050° C., aluminium alloys may be treated in nitrates used over the range 400°–525° C., and steel may be given an isothermal heat treatment using two baths, one for austenitising and the other for quenching and holding. A comparatively new type of salt bath is in use for the descaling of steels, particularly high-alloy steels. The salt in this case is molten caustic soda at temperatures of about 370° C. By treatment of sodium with cracked ammonia in a container dipping into the bath a concentration of sodium hydride may be maintained in the caustic soda. The hydrogen reacts with surface oxides on the charge and a clean surface is obtained after the charge has been water-quenched.

The electrodes in the electrode salt bath usually comprise 2 in. square straight steel bars connected to a low-voltage supply. The salt container may be either metallic or refractory; it is usually metallic for low-temperature

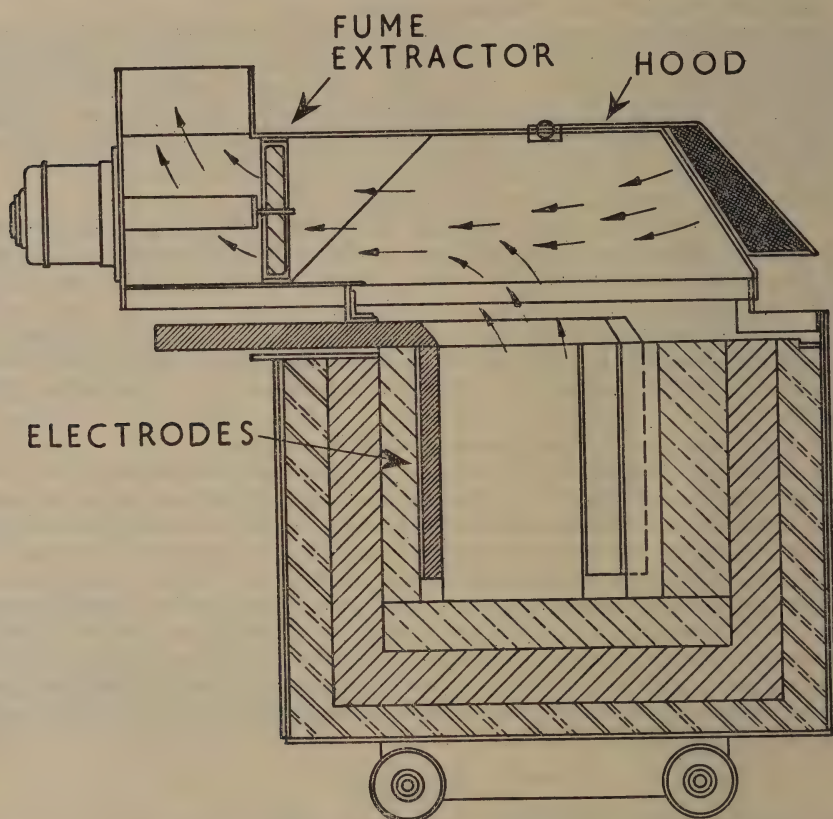


FIG. 19. Electro salt-bath furnace.

treatment and for cyanide salts and refractory for medium and high-temperatures or where neutral salts are used.

The advantages of salt baths lie in speed and uniformity of heating, freedom from distortion of the treated parts and the small furnace bulk, absence of scaling and decarburization.

THERMAL ECONOMY AND FURNACE OPERATION

Some precautions which should be taken in the operation of each of the above types of furnace with a view to heat economy are now referred to.

HIGH FREQUENCY INDUCTION FURNACES

The small body carrying the charge makes these furnaces excellent for intermittent operation, but when they are operated in this manner great care should be taken to avoid heavy no-load losses in electrical plant left running. It is important to switch the condensers off when the furnace is not in use.

Where successive melts are carried out, the time between charges should not exceed 15–20 minutes. For delays of 30 minutes or over, however, the converting equipment should always be shut down.

It is usually practicable to have two equal-sized furnace bodies operating off one generator and the supply fed to either by a simple change-over switch. It is then possible to keep the power on as long as melting has to be carried

out, as teeming from one body and recharging takes place while the other is in service. It is necessary to ensure that the liner is properly patched after each heat, a very necessary precaution with the thin walls used.

The general overall efficiency of High Frequency Induction equipment when applied to heat treatment processes is of the order of 35–40 per cent., i.e. actual input to the work itself. As the power to the inductor is switched on only as required, the losses are a function of the standby power requirements of the oscillator. The following may be taken as a guide for standard valve generators:

- 30 kW. input—standby losses 2.0–2.5 kW.
- 10 kW. input—standby losses 1.2–1.4 kW.

LOW FREQUENCY INDUCTION FURNACES

These furnaces frequently work in pairs, or more rarely singly, off a Scott-connected transformer. Care should always be taken to see that the installation is so arranged and operated that the transformer is properly utilized. It is even more important to ensure continuity of operation. A certain amount of molten metal must be left in the base of the furnace after each charge has been poured to act as the secondary of the transformer for the next charge. (When starting up, molten metal must be poured in initially and this metal must be kept molten.) Between 10 and 20 per cent. of the transformer rating is required to ensure that the metal does not solidify, and this represents a serious heat loss which can be avoided only by keeping the furnace in constant use. Where long shut-downs are necessary the furnace should be completely emptied rather than the supply kept on to keep the priming charge molten.

Radiation, particularly from the top of the furnace, is again a serious source of loss. This can be minimised by the use of covers, the cost of which is warranted when the reduction in losses is taken into account.

The heat balance per melt should be of the following order:

	Per cent
To the charge	65
Electrical losses	5
Radiation, etc.	25–35
Stand by losses	depend on time out of service.

ARC FURNACES

Intermittent operation is one of the most serious causes of loss of heat in an arc furnace. The large mass of material making up the furnace radiates heat quickly when left idle, and this heat has to be restored when the furnace is re-started. An arc furnace should therefore run continuously and the charging time should be reduced to a minimum. It is preferable to use a smaller furnace (if ingot sizes allow of it) and keep it in continuous operation for 168 hours a week rather than a slightly larger furnace for say 120 hours.

The charging time can be much reduced by having a movable roof. The swinging of the roof allows practically all the charge to be dropped in from one or two baskets in ten minutes instead of being fed by hand or mechanical charger from the side in from half an hour to three-quarters of an hour. If conditions do not allow of a movable roof being installed, mechanical charging is usually preferable.

No matter how inserted, each charge should be ready for immediate feed as soon as the previous charge is teemed, and any patching to the liner that may be required has been done. The necessary material for liner and roof repairs should be lying ready to hand and staff standing by to begin operations as soon as the furnace is available.

Upkeep of the furnace is important, particularly at doors and at the electrode holder, where care should be taken to see that the joints are tight. Reduction of radiation loss by these methods not only reduces heat consumption but prolongs the life of the liner and reduces electrode consumption.

Special attention should be paid to the water cooling of the electrode holders, especially to ensure that the water supply does not foul the tubes; this would incur greater power for circulating the water, increased heat loss due to easier conduction along the electrode, and higher electrode consumption.

On the electrical side special care should be given to the maintenance of the circuit breaker or switch, as this operates many times a day—the duty being far more onerous than for ordinary industrial purposes; and, apart from the potential risk to life of a faulty switch, damage thereto may hold up production for an appreciable time, which again results in heat losses during the idling period. Manufacturers will give instructions regarding the frequency with which switch contacts and oil need attention, depending on the design of the switch and the severity of service.

The following is an approximate heat balance of a good modern furnace when melting :

						<i>Per cent.</i>
To the charge	..	..	..	..	..	62*
Electrical losses	..	..	..	..	..	9
Cooling water	..	..	..	..	..	4
Radiation, door loss and conduction	..	..	..	..	..	25

*376 units per ton when melting steel.

The electrode consumption should be of the order of 14 lb. per ton (graphite) or 28–30 lb. per ton (amorphous carbon).

RESISTOR FURNACES

The electricity consumption of a heat treatment furnace is made up of the following :

- (a) heat absorbed by the charge;
- (b) heat absorbed by work carriers, supports, containers, bells, liners, conveyors, belts, etc., to accommodate the charge;
- (c) general furnace losses;
- (d) heat losses occurring during loading and unloading the charges.

The total heat losses are made up of (b), (c) and (d) above; consequently these must be kept to a minimum if maximum efficiency is to be achieved.

The following notes give some general information on these sections:

- (b) The heat absorbed by work carriers depends to a large extent on the nature of the charge, and it is usual for furnace makers to design specific work carriers to suit such charges. It is preferable to use a furnace designed specifically for the work to be undertaken, though that is not always possible. The use of flimsy work carriers in order to obtain minimum heat absorption on the carriers, at the expense of every other consideration, is unjustifiable and sure to cause serious trouble, for example, when heat-treating long, slender articles in a vertical furnace, it is essential to design the jigs to give adequate support, so that if hardening is the heat-treatment operation the parts show minimum distortion after quenching.
- (c) General furnace losses. Reducing these is a matter of good design, selecting refractory and insulating materials to give minimum heat losses over specified temperature ranges consistent with other essential factors

(such as heating-up time and maximum operating temperature). In batch furnaces the greatest heat loss occurs at the door; it is usual so to design that the furnace vestibule is restricted to the minimum consistent with the work to be treated and that the door itself fits the front case of the furnace snugly.

- (d) Losses due to loading and unloading of the charges. These can be minimised by well-known means, such as the use of continuous furnaces. In the larger continuous furnaces, particularly those of the "double-deck" type, recuperation by interchange is employed. This principle cannot be employed to advantage in the smaller continuous furnaces.

Using the standard horizontal batch-type furnaces, it is neither possible nor desirable to use heat recuperation. Attention paid to the careful opening of the door during loading and discharging will, however, reduce door losses.

With bell-and-retort furnaces, particularly those using protective atmospheres, recuperation between purged, cold charges and hot charges cooling down can be used to advantage.

ELECTRICITY SUPPLY AND FURNACE OPERATION

Electrical installations and the operation of furnaces must be managed with due regard to the economic use of the supply, whether public or private. Limitations may be more severe in the latter case, but in the former tariffs are usually designed to encourage limitations of the peak demand.

The most troublesome load is that of the arc furnace during the melting period. If several furnaces are installed much effort should be directed to staggering the melting periods, thus avoiding a higher maximum demand and so, in turn, achieving more economic running of the station supplying the power. The peak demand may also be reduced by instructing the operatives not to shorten the melting time by running on a high voltage tap before an arc can be properly maintained. It is seldom that the melting time can be appreciably shortened, and the total consumption is actually increased by this practice, owing to the very heavy demand each time the arc is struck after being extinguished.

Where melting only is done in the furnaces, one group (consisting of one or more units) should be allowed to complete about half of the melt before the next is brought in—though this action should not be carried so far as to involve delay in any group and bring about the worse condition of heavy radiation losses.

If refining as well as melting is being done, still more can be done to avoid heavy loadings, provided that the length of the refining period is known. In any event, careful planning can make a big reduction in the calls on the electricity supply.

Both high and normal frequency furnaces have regular load curves, but their cycle times are short and (except for the stand-by losses inherent in low frequency furnaces) they are particularly suitable for fitting in "valleys" in load curves and thus ensuring smoother boiler loading. Where the output requirements of the factory allow of intermittent furnace operation, this procedure should be adopted; and low frequency furnaces should be emptied if the stand-by period is likely to be of some hours duration, but the supply should be maintained on the furnaces coupled to one transformer so that there is a supply of molten metal immediately available for the other furnaces when these are re-started.

Resistor furnaces should be heated up wherever possible at times of low load elsewhere, provided that they are not then required to stand idle for some time until they receive their first charge.

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CHAPTER 23

REFRACTORY AND INSULATING MATERIALS

REFRACTORY MATERIALS

THE subject of refractory materials is so vast that it would be impossible to do full justice to it within the scope of this book. Many interesting problems concerning the use, manufacture and behaviour of even the commonest refractory materials are still the subject of research. There are equally many problems of a more specialist nature that may be solved by the use of less common refractories. Considerations of space make it necessary to concentrate on those properties of refractory materials that affect every-day practice and in particular influence the efficient use of fuel.

The influence of refractories on fuel economy arises from many causes, among which may be mentioned:

- (1) The stability of the furnace structure is obviously an essential feature in the efficient performance of industrial operations.
- (2) Maintenance of a sound construction free from cracks within the bricks or the joints is essential. Cracks in the brickwork may cause short circuiting of flue gases or leakage of live gas into the air or air into the gas, with disastrous effects on temperature uniformity in the furnace, on the amount of fuel used and on the brickwork; this is particularly important in coke ovens and gas retorts.
- (3) The action of slag on furnace brickwork may be such as to destroy it. In extreme circumstances it may give rise to holes through furnace walls, for example into the heating flues.
- (4) Correct thermal gradient is also important; in many firing operations bricks tend to wear down to a limiting thickness, no matter how thick they may be originally.
- (5) In continuously-operated furnaces the longer the periods between cooling down for repairs the less fuel is needed for heating up the furnace from the cold. On the other hand, planned maintenance may be more economical even though it may mean doing repairs sooner than they are, strictly speaking, required.
- (6) In many industrial operations heat has to be transmitted through a wall of refractory material, and in all furnaces a great deal of heat is stored within the bricks. Their thermal properties, therefore, affect the quantity of fuel used and are of considerable interest to the furnace operator.

TYPES OF REFRACTORIES

The following are the commoner types of refractories:

Silica brick—contains at least 92 per cent. of silica; bricks of this type are normally bonded with a small amount of lime.

Siliceous brick—contains from 85–92 per cent. of silica, the remainder being essentially alumina.

Semi-siliceous brick—contains 78–85 per cent. of silica, the remainder being essentially alumina.

Firebrick—a brick that, in the fired state, consists essentially of aluminosilicates and silica, with less than 78 per cent. of silica and less than 38 per cent. of alumina.

TABLE 1. TYPICAL PERCENTAGE COMPOSITIONS OF REFRACTORY MATERIALS

Constituent of brick	Type of Brick								
	Firebrick	Aluminous firebrick	Siliceous or semi- silica brick	Silica brick	Sillimanite brick	Magnesite brick	Chrome- brick	Chrome magnesite brick	Dolomite brick (stabilised)
Silica—SiO ₂	55-70	50-55	84-86	94-96	25-35	2-5	3-10	3-10	12-15
Alumina—Al ₂ O ₃	25-38	38-45	11-13	0.5-1.5	55-65	1-4	10-25	5-15	2-3
Titania—TiO ₂	1-1.5	1-2	0.5-1	0.2-0.5	0.5-1	tr	tr	tr	tr
Iron oxide—Fe ₂ O ₃	2-5	2-4	1-1.5	0.5-1.5	0.5-1.5	2-8	12-20	8-15	2-4
Chromic oxide—Cr ₂ O ₃	—	—	—	—	—	—	35-45	20-35	—
Magnesia—MgO	0.2-0.8	0.2-0.6	0.2-0.5	0.1-0.5	0.5-0.8	84-92	15-35	40-60	38-42
Lime—CaO	0.5-1	0.4-0.8	0.2-0.5	2-2.5	0.5-1	2-4	2-3	1-3	38-42
Alkalies—K ₂ O + Na ₂ O	1-2	0.5-1	0.5-1	0.2-1	0.5-1	0.1-0.5	tr	tr	tr

Aluminous firebrick—contains from 38–45 per cent. of alumina, the remainder being essentially silica.

The accepted names of other types of refractory give a sufficient indication of their general composition, e.g. magnesite brick, chrome brick, chrome-magnesite brick, silicon carbide brick, sillimanite, etc.

Typical compositions of refractory materials are given in Table 1.

RAW MATERIALS

In Britain there are abundant raw materials for the commonly-used refractories—firebricks and silica bricks. Fireclays, from which firebricks are made, are associated with the coal measures throughout the country; they vary in composition from siliceous plastic materials to hard bauxitic shales (Ayrshire). Fireclays are thus available for all purposes. Ganister and quartzite rocks, consisting of over 97 per cent. of silica, also occur widely in the Carboniferous strata; these are worked for brickmaking in the Sheffield district, in North and South Wales, in Durham and in Scotland. Quite recently, a deposit of flint occurring in Norfolk has begun to be used as a raw material for silica bricks.

Magnesite does not occur in Britain. It occurs elsewhere in Austria, Czechoslovakia, Greece, Manchuria, India, South Africa, Russia and other countries. A process has been developed for the extraction of magnesia from sea water by precipitation with lightly burned dolomite; this process is used to supply most of the magnesia required in Britain for brickmaking. It is also used for making magnesium oxychloride products, examples of chemical bonding materials referred to below (p. 600). Dolomite is plentiful in Britain and is used in the making and fettling of steel furnace hearths and, when partly or wholly stabilised, as bricks for furnace construction and maintenance.

Chrome ore occurs only in minor quantities in Britain, the chief indigenous sources being the Island of Unst in Shetland; the major world deposits occur in Turkey, Greece, Yugoslavia, South Africa, India, Russia, Cuba, the Philippines and New Caledonia. Raw materials for special refractories such as sillimanite, bauxite, zirconia, etc., are not found in Britain, at least in substantial quantities.

MANUFACTURE

Some knowledge of the general processes of manufacture of refractory materials is of great help in understanding their properties. If furnace designers were familiar with the difficulties of shaping and drying large and intricate shapes, they would probably try to use simpler and smaller designs; sharp re-entrant angles would be avoided wherever possible owing to the stresses and dangers of cracking in bricks and blocks having such angles.

In the manufacture of firebricks the raw materials are submitted to preliminary treatments such as mixing, grinding and screening. The subsequent processes vary to suit the type of clay and product. In the normal plastic process, grog, i.e. graded, burnt, refractory material, is worked into the clay, and the bricks are shaped by hand-moulding, extrusion or pressing. Dry-pressing consists in subjecting the clay and grog, at low moisture content, to a high pressure, the plasticity of the clay playing a less important part. The clay may be de-aired before or during shaping; this removal of entrapped air leads to the production of a dense brick.

The "green" (i.e. unfired) bricks are dried on a hot floor, or in a chamber or tunnel drier. (Chapter 25.) The removal of water leads to shrinkage, and unless carried out under controlled conditions is liable to cause stress and distortion, if not actual cracking. Drying difficulties are particularly marked

when dealing with large intricate shapes. The dried bricks are fired in intermittent or continuous kilns at a temperature depending on the nature of the clay, and chosen to give a strong product reasonably free from subsequent contraction.

Ground ganister or quartzite, being almost completely devoid of plasticity, requires a different moulding technique for the manufacture of silica bricks. The rock is crushed and graded, and is then mixed with milk of lime and a temporary bond in an edge-runner mill. The temporary bond, an organic material such as sulphite lye, gives some strength to the "green" bricks, enabling them to be handled without damage to the corners and edges; the milk of lime forms the final bond in the fired product, dissolving some silica and forming, together with the impurities, a strong matrix. The moulded bricks are dried and then fired at a high temperature. The firing process in silica brick manufacture leads to a set of reactions quite different from those that occur in firing clay. Silica can assume a number of different crystalline forms. It normally occurs in nature as quartz, but this changes during firing to other crystalline forms having different physical properties. These other forms of silica—cristobalite and tridymite, are discussed below.

Most other refractory raw materials resemble quartz in their rock-like nature. In consequence of their lack of plasticity the production of bricks from them depends either on the addition of sufficient clay to make moulding possible or on the use of a high *forming pressure*. Sillimanite bricks are made by the first method or by a combination of the two; chrome-magnesite and dolomite bricks are shaped under pressure without clay addition. Pre-calcination of the base material may be necessary, and may exert a profound effect on ultimate properties, e.g. in the manufacture of refractories from kyanite, a mineral of the same composition as sillimanite but of different physical properties and occurring more abundantly.

Two other methods occasionally used for making refractories are worth noting. The first, *chemical bonding*, is sometimes used in the production of certain basic refractories; the bricks are not fired, their strength being developed in the cold by chemical action. Chrome-magnesite bricks made in this way generally have a higher resistance to *spalling* (splitting off, chipping) and have been successfully used in metallurgical furnaces. In the special second method the raw materials are treated rather like a metal, being fused and cast into moulds. This technique is difficult and expensive, owing to the very high melting-points of the materials to be fused, but it brings the constituents into a state of equilibrium and enables crystallization to develop. Fusion casting has been used with conspicuous success in the production of mullite tank blocks for the glass industry.

CONSTITUTION

The constitution of the refractory material has a major influence on its chemical and physical properties, and hence on its durability. Clays consist of a number of hydrous aluminosilicate minerals which break down on heating, and after passing through a somewhat ill-defined intermediate stage, tend to form the only compound of alumina and silica stable at high temperatures, namely *mullite* ($3\text{Al}_2\text{O}_3, 2\text{SiO}_2$). X-ray examinations of clays fired at increasingly high temperatures shows that mullite begins to develop at about $1,000^\circ\text{C}.$, though the crystals are then too small to be seen under the microscope.

Fired clay bricks contain much fused material (glass) together with varying amounts of mullite. In addition, most firebricks contain quartz grains; these are not in equilibrium with the mullite or the glass, but their solution by the glass is extremely slow; even after a firebrick has had prolonged use at high

temperature, quartz may still be present. It is, however, on the mullite development and the glassy bond present that high temperature strength, resistance to slagging, and other properties largely depend.

The subject of the different crystalline forms of silica is specially interesting and of importance in the manufacture of refractories. At ordinary temperatures, silica can exist in three principal crystalline forms: (a) quartz, (b) cristobalite, and (c) tridymite. Furthermore, quartz and cristobalite both have two crystalline forms and tridymite has three—making seven modifications in all. The crystalline varieties of silica are formed from one another during heating and cooling, according to the scheme shown in Table 2.

TABLE 2. TRANSFORMATIONS OF THE SILICA MINERALS

Temp. °C.		Linear change on increasing temp. Per cent.	Velocity of reaction	Notes
1,800	-1,713	cristobalite melts		
1,700				
1,600	-1,470	β -quartz \rightarrow β -cristobalite	+ 4.85	Rather slow at 1,470° C., increases as temp. rises.
1,500		Also β_2 -tridymite \rightarrow β -cristobalite	- 0.65	
1,400	-870	β -quartz \rightarrow β_2 -tridymite	+ 5.5	Between 870° C. and 1,470° C. β_2 -tridymite is the stable form and is slowly formed from cristobalite and quartz.
1,300				
1,200				
1,100		β -cristobalite \rightarrow β_2 -tridymite		
1,000				
900				
800				
700				
600				
-573		α -quartz \rightarrow β -quartz	+ 0.45	Instantaneous.
500	-250	α -cristobalite \rightarrow β -cristobalite	+ 1.05	Instantaneous.
400				
300	-165	β_1 -tridymite \rightarrow β_2 -tridymite	+ 0.06	Instantaneous.
200	-117	α -tridymite \rightarrow β_1 -tridymite	+ 0.15	Instantaneous.
100				
0				

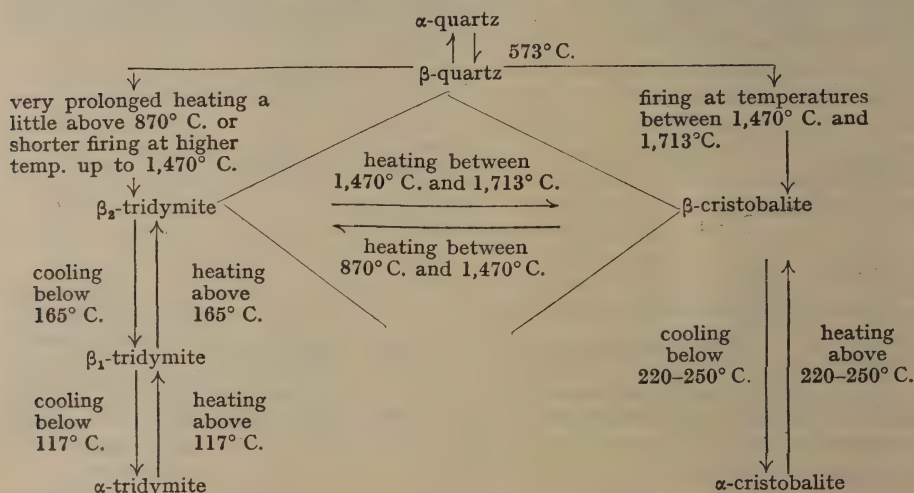
Arrows indicate the direction of the change with rising temperature.

In using Table 2 the reader should imagine that he is starting with a brick containing all three minerals—quartz, cristobalite, and tridymite—and that

this brick is built into a furnace, which is heated up to working temperature. By proceeding up the temperature scale he can easily follow the changes that occur as the structure is heated and understand the volume changes to which they give rise.

Table 3 gives the conventional way of expressing these changes. The reversed arrows signify reversible transformations that occur during heating and cooling respectively.

TABLE 3. TRANSFORMATIONS OF THE SILICA MINERALS



The forms α and β are sometimes referred to as the *low* and *high* modifications. The different modifications of the three main crystalline varieties of silica form practically instantaneously when that variety is heated at the temperatures stated, but the change from one main variety to another, e.g. from quartz to cristobalite, is much slower. The significance of these changes to the user of silica bricks lies in the considerable changes in volume that accompany certain of these transformations.

In the unfired state a silica brick consists of α -quartz; when this brick is placed in the kiln and fired, the first change is to β -quartz at 573° C., accompanied by a linear expansion of about 0.45 per cent. The volume expansion may be taken as three times the linear expansion (i.e. about 1.35 per cent.). At higher temperatures, particularly when the added lime begins to form a viscous bond, some of the β -quartz is dissolved, and it is later precipitated as cristobalite or tridymite depending on the temperature conditions. In the fired brick we thus have varying amounts of quartz, tridymite, and cristobalite.

When such a brick is used in a furnace lining, the following sequence takes place: on warming up the furnace, the α -tridymite suddenly changes to β_1 -tridymite at 117° C. (i.e. only a little above the boiling-point of water); sudden linear expansion equivalent to about 0.15 per cent. occurs. At 165° C., the β_1 -tridymite undergoes a further transformation but the expansion is small. In the range 220-250° C. the α -cristobalite suddenly changes to β -cristobalite, the exact temperature of this change depending on the thermal history of the cristobalite. This cristobalite change is the most serious from the standpoint of spalling, because the linear expansion is over 1 per cent. On further heating, any unchanged quartz suffers transformation at 573° C., with a volume change of the order previously noted. Above this temperature, the expansion of a silica brick is small and regular unless much residual quartz is present. The

quartz is converted into tridymite and/or cristobalite during use, and if sufficient quartz is present permanent growth of the brickwork is likely to occur. The close relationship between the mineral constitution of silica bricks and their sensitiveness to thermal shock at low temperatures will be evident; the subject is further referred to below, in the section on *spalling* (p. 615).

Magnesite bricks have a relatively simple constitution. On dead-burning, natural magnesite (magnesium carbonate, MgCO_3) loses carbon dioxide and develops crystals of periclase (magnesium oxide, MgO). This is the only crystalline form of magnesia, but during continued firing the crystals tend to grow. The matrix of magnesite bricks varies according to the nature of the impurities in the raw material; if siliceous, forsterite ($2\text{MgO}, \text{SiO}_2$) may be formed; if both siliceous and calcareous the matrix may approximate to monticellite ($\text{CaO}, \text{MgO}, \text{SiO}_2$). Iron oxide can enter the periclase grains in solid solution or can form magnesio-ferrite ($\text{MgO}, \text{Fe}_2\text{O}_3$).

Chrome and chrome-magnesite refractories have a particularly complex constitution. Chrome ore consists of a complex *spinel*, which may be written $(\text{Fe}^{II}, \text{Mg})\text{O}, (\text{Cr}, \text{Al}, \text{Fe}^{III})_2\text{O}_3$, together with gangue, usually siliceous. Laboratory work has thrown fresh light on the nature of the chemical changes that occur when a chrome ore is fired. The ferrous spinel constituents are oxidized at quite a low temperature (300°C.) and a sesquioxide solid solution is formed; magnesian spinels remain unaffected. If, at the higher temperature of kiln firing, some reduction occurs—as is frequently the case under industrial firing conditions—the sesquioxide solid solution is reduced back to the spinel and a marked increase in volume occurs. If this takes place, the fired bricks may be friable.

Dolomite, the double carbonate of lime and magnesia ($\text{CaCO}_3, \text{MgCO}_3$) breaks down when heated, to form the two oxides (CaO, MgO). On exposure to the air, the lime (CaO) takes up moisture (becomes *slaked*) and the mass soon disintegrates. To overcome this, dolomite is stabilised by firing it with a siliceous material, serpentine for example, whereby the lime of the dolomite combines with silica in the serpentine to form chiefly tricalcium silicate. Consequently a stabilized dolomite brick consists mainly of periclase and tricalcium silicate; some calcium orthosilicate, calcium ferrite and brown-millerite ($4\text{CaO}, \text{Al}_2\text{O}_3, \text{Fe}_2\text{O}_3$) may also be present in small amounts.

Sillimanite bricks are made from one or other of the sillimanite minerals, viz., sillimanite, andalusite and kyanite. These three minerals all have the composition $\text{Al}_2\text{O}_3, \text{SiO}_2$, but different physical properties. In particular, they break down at different temperatures when heated; the expansion accompanying this breakdown is different for each mineral, but the final product is the same, mullite and cristobalite being formed. Consequently, fired sillimanite bricks consist of a mass of mullite needles in a siliceous (cristobalite) ground-mass (matrix). Commercial sillimanite bricks in Britain are manufactured chiefly from calcined kyanite, though the sillimanite deposits of Assam are also being exploited.

Other types of refractories are not generally so important. Silicon carbide bricks may consist almost entirely of that (artificial) mineral—as in re-crystallized bricks—or may contain a proportion of clay as bond—as in clay-bonded bricks. Forsterite refractories are composed essentially of crystals of olivine $2(\text{Mg}, \text{Fe})\text{O}, \text{SiO}_2$. Alumina bricks consist mainly of corundum. In addition, there are available zircon bricks—consisting of zirconium silicate—and small special articles for use at very high temperatures are sometimes made of zirconium oxide, thoria, beryllia, etc. A new composite type of refractory recently developed consists of a pressed mixture of a highly refractory oxide or carbide and metal; these products (“cermets”) have been

produced for high-temperature engineering purposes.

REFRACTORY PROPERTIES

Few, if any, refractory materials have sharp melting-points; because of their complex nature they normally have a *softening range*. This is particularly true of fireclay products, as will be readily appreciated by reference to the Al_2O_3 - SiO_2 equilibrium diagram (Figure 1). This may be taken to represent the equilibrium relationships of fireclays, siliceous bricks, sillimanite and

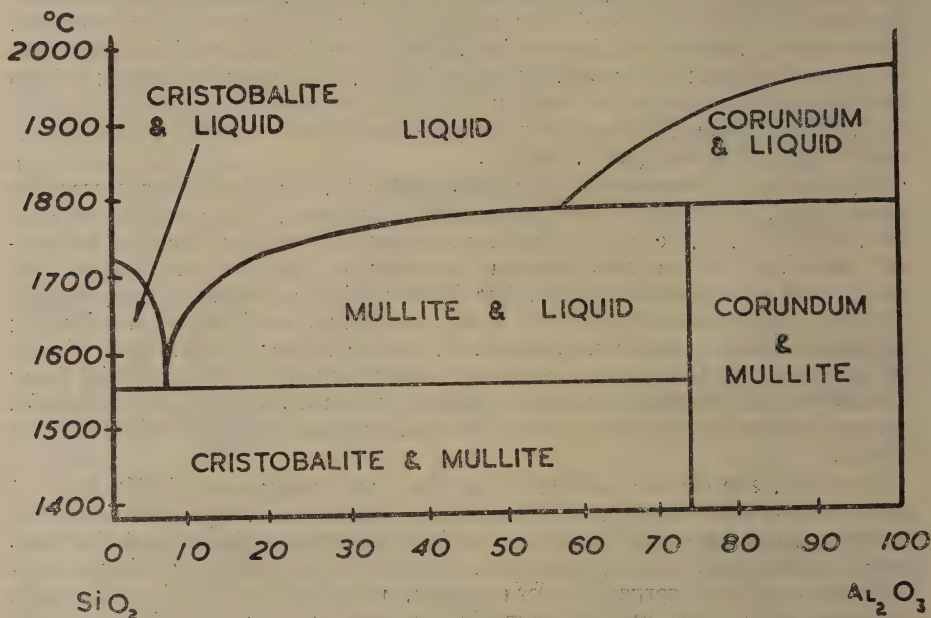


FIG. 1. Alumina-silica equilibrium diagram.

alumina bricks; any error introduced by small proportions of fluxes may be considered to lead merely to a general lowering of the softening temperatures. The fusion relationships of silica bricks cannot be considered on the basis of this diagram owing to the presence of an important, though small, amount of lime; it may, however, be stated that the presence of much alumina in a lime-bonded silica brick is particularly detrimental in its effect on the fusion and slagging of the brick.

Firstly, the eutectic composition is: 94.5 per cent. silica, 5.5 per cent. alumina, the solidification point being 1,545° C.

This suggests how important is the absence of alumina in the raw material used for silica brick production; in the presence of lime the eutectic temperature is still further depressed to 1,170° C. Siliceous bricks containing about 80 per cent. SiO_2 are well past the eutectic composition, but in all alumino-silicate refractories containing less than 72 per cent. Al_2O_3 , some liquid will form at some temperature below 1,545° C. (below the binary eutectic temperature owing to the presence of impurities such as lime, magnesia, iron oxide, alkalis, etc.). The proportion of liquid will increase with rising temperature until eventually the whole mass is fluid.

REFRACTORINESS

At some temperature between that at which liquid first forms and that at which the whole brick is fluid, the proportion of liquid will be such that the brick cannot support its own weight and it will slowly deform. If the test piece

is in the form of a pyramid, 1½ inch high on a triangular base of ½-inch side (one edge of the pyramid being perpendicular to the base), and the specimen is heated at the rate of 5° C. per minute, the temperature at which the test piece has bent until the tip is level with the base is called the "refractoriness". The temperature at which this will occur evidently increases with increasing alumina content (see Table 4).

A sillimanite or high-alumina brick containing over 72 per cent. Al₂O₃ will not form liquid at 1,545° C.; no liquid will be produced (neglecting the fluxes present) until a temperature of 1,810° C. has been reached. At this temperature any mullite present decomposes into corundum and a liquid. The high refractoriness of sillimanite bricks is therefore readily explained. Most other refractories have a fusion point (refractoriness squatting value) above that at which normal furnaces are operated (see Table 4).

TABLE 4. AVERAGE REFRACTORINESS SQUATTING VALUES

Brick	British cone No.	Temperature equivalent ° C.	Brick	British cone No.	Temp. equiv. ° C.
Silica	32-33	1,710-1,730	Sillimanite ..	35	1,770
Siliceous	29-31	1,650-1,690	Magnesite ..	>38	>1,850
Firebrick (23-30% Al ₂ O ₃) ..	27-29	1,610-1,650	Chrome	>38	>1,850
" (30-35% ") ..	28-31	1,630-1,690	Silicon carbide*	>38	>1,850
" (35-40% ") ..	29-33	1,650-1,730	Carbon † ..	>38	>1,850
Aluminous firebrick	32-35	1,710-1,770	Zirconia	>38	>1,850

* Begins to decompose at lower temperatures.
† Decomposes unless atmosphere is strongly reducing.

Refractoriness-under-load

The refractoriness of a product is often of less importance than the *refractoriness-under-load*. In all furnace construction the brickwork is subjected to stress; this may arise from the weight of the superincumbent brickwork, by the thrust of an arch, or by pinching due to inadequate expansion allowance. This stress may cause the bricks to deform at a temperature much below their fusion point. The effect is particularly marked in firebricks. Under a load of 28 lb. per square inch (the standard adopted in testing this type of brick, and equivalent to 2 kg. per square centimetre), 5 per cent. subsidence will generally occur at a temperature about 200° C. below the fusion point. Subsidence commences at an even lower temperature, the failure being one of slow deformation. In contrast, silica bricks maintain their strength practically up to their fusion temperature. This is attributed to the network of cristobalite and tridymite which maintains its rigidity even when the interstitial matter has become liquid; when the network of cristobalite crystals itself breaks down, the brick shears suddenly. Figure 2 shows typical results on a silica brick and a firebrick.

Magnesite and chrome bricks also generally shear under load; the temperature at which this occurs may be as much as 500° C. below their fusion point. This may be due to the cubic crystal structure of periclase and spinel, a structure inimical to crystal inter-growth; hence when the matrix of such bricks softens the whole mass loses strength.

In chrome-magnesite bricks, this weakness has to some extent been overcome. Some of the magnesia combines with the siliceous gangue of the chrome ore to form forsterite; this mineral, when pure, does not melt until 1,890° C., and if a network of forsterite can be developed within a chrome-magnesite brick the refractoriness-under-load is improved in a remarkable manner.

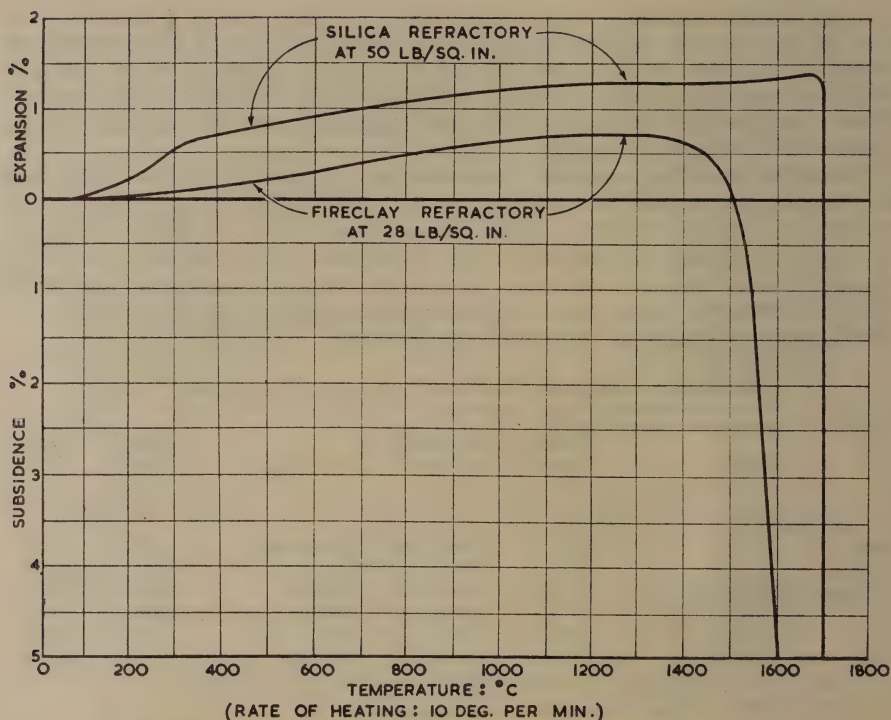


FIG. 2. Refractoriness-under-load curves for fireclay and silica refractories.

Sillimanite bricks have good mechanical strength at high temperatures since little of the Al_2O_3 - SiO_2 eutectic is present and the mullite crystals are needle-shaped and form a strong intergrowth. Some comparative data on the refractoriness-under-load of various types of refractories are given in Table 5. It should be remembered that in practice only one face of a brick is usually at the highest temperature, so that frequently the colder part of a brick can support a load when the temperature of the working face is such that the brick would be expected to collapse.

TABLE 5. AVERAGE REFRACTORINESS-UNDER-LOAD VALUES

Brick	Refractoriness-under-load* (28 lb./sq. in.)	
	Cone	° C.
Silica	29-32	1,650-1,710
Siliceous	20-27	1,530-1,610
Firebrick (25-30% Al_2O_3)	13-16	1,380-1,460
" (30-35% ")	16-19	1,460-1,520
" (35-38% ")	19-26	1,520-1,580
Aluminous firebrick (38-45% Al_2O_3)	26-28	1,580-1,630
Sillimanite	>29	>1,650
Magnesite	18-28	1,500-1,630
Chrome	12-16	1,350-1,460
Chrome-magnesite	18-32	1,500-1,710
Silicon carbide	>34	>1,750
Carbon	>34	>1,750
Zirconia	18-20	1,500-1,530

* Indicated by the temperature at which collapse occurs.

Texture. The texture of a refractory is a property difficult to define; it involves a knowledge of the volume and nature of the pore system in relation to the solid material, the size and orientation of the grog particles, and the presence or absence of making faults. The texture has a bearing on the refractory properties, resistance to spalling, abrasion and slagging, and the thermal conductivity. Some measure of this property is given by the porosity and permeability to gases, but even with these data the texture is not fully defined.

In fireclay products, the texture is controlled by the grain size of the clay, the nature and grading of the grog, and the temperature and duration of firing. Fineness of grain favours vitrification. A fine textured firebrick may, therefore, be expected to soften under load at a slightly lower temperature than a coarse product of similar composition. The abrasion resistance of a fine-textured brick is usually high. The relationship between the spalling tendency and the texture is complex. It has generally been considered that a fine textured refractory will be more sensitive to sudden changes in temperature than a coarse textured product. This is not invariably true, however, for the process of manufacture has a modifying influence: with the dry process, for example, it is possible with some clays to develop a close texture which is still resistant to spalling. The relationship between the texture and the thermal properties will be noted later.

It is difficult to give porosity and permeability values which may be looked on as typical of various types of brick. The porosity of firebricks, for instance, may vary from about 12 to 25 per cent. or more; that of silica bricks from about 20 to 30 per cent.

SPECIFIC GRAVITY

The true specific gravity of the material composing a brick, as distinct from the bulk density of the brick as a whole (i.e. including the pore spaces), is of special significance only for silica bricks and magnesite bricks. This is due to the comparatively constant composition of these products and the important differences in specific gravity between the various forms of silica in the one, and the increase in specific gravity with periclase development in the other.

Quartz has a specific gravity of 2.65; cristobalite, 2.33; tridymite, 2.28. From what has already been said in the section on constitution, it follows that the specific gravity of a silica brick is a good guide to the degree of conversion. This does not apply to the siliceous class of refractories. A silica brick of specific gravity 2.45 evidently contains a considerable amount of unconverted quartz, which is likely to cause permanent growth during use. The specific gravity of most present-day silica bricks lies between 2.32 and 2.37, indicating adequate quartz conversion to cristobalite and tridymite. It is not possible to assess the relative amounts of cristobalite and tridymite in a silica brick by a specific gravity determination; for this purpose X-ray, micro-examination and/or thermal expansion measurements are necessary.

The fact that the density of magnesia increases with the heat treatment has been used as a method of assessing the adequacy of the kiln firing of magnesite bricks. In the past, the figure 3.65 has usually been considered the maximum value to which a magnesite brick in which the periclase crystals are fully developed will attain. The present view is that this figure is somewhat high and should be modified according to the chemical composition of the brick tested, a high iron oxide content increasing, and a high silica content decreasing, the actual value.

The specific gravity of a firebrick is of little significance, owing to the complex nature of the material. Some typical data on the specific gravity of refractories are given in Table 6.

TABLE 6

Type of brick	True sp. gr.	Bulk density	Weight of bricks lb./cu. ft.
Silica	2.3-2.4	1.7-1.8	105-115
Siliceous	2.5-2.6	1.8-2.0	115-125
Firebrick	2.5-2.6	1.9-2.1	120-130
Bauxite	3.1-3.4	1.8-2.1	115-130
Magnesite	3.5-3.6	2.7-2.9	165-180
Chrome	3.7-4.2	2.8-3.5	170-220
Zirconia	4.8-5.9	4.0-4.6	250-275
Carbon	2.7-3.1	1.9-2.0	120-125
Sillimanite	2.9-3.1	2.0-2.2	125-135
Silicon carbide	3.0-3.2	2.4-2.6	150-165

EFFECT OF RE-FIRING ON THE VOLUME STABILITY

The changes that occur during the firing of refractory materials belong to the class known as *arrested reactions*, in which the chemical and physical changes are stopped before they have gone to completion. For example, during the firing of firebricks most of the reactions taking place result in a certain amount of contraction; if these reactions are not sufficiently completed, contraction may continue during use. If such *after-contraction* is considerable, the masonry of the furnace will tend to be displaced, open joints, cracks and distortion resulting. For most types of fireclay products, an after-contraction of 1 per cent. after re-firing for two hours at 1,400° C. is considered high; the temperature at which a brick should be tested and the allowable after-contraction must depend on the conditions of service.

With silica bricks, the kiln treatment leads to expansion, but here again the reactions are generally arrested before completion. During use at high temperatures, the residual quartz may be converted into the forms of lower density, i.e. greater volume, and growth may thus occur. This growth may take place even against high compressive forces, hence it is essential that the after expansion of a silica brick should be low—usually less than 0.5 per cent. when fired for two hours at 1,450° C.

Magnesite shrinks during firing owing to the continued growth of the periclase crystals. Chrome and chrome-magnesite bricks may contract or expand, the kiln atmosphere playing a determining part with bricks containing chrome ore. Adequate firing is always necessary to take the reactions as near to completion as is practicable.

THERMAL PROPERTIES

THERMAL EXPANSION

To the furnace builder, the ordinary or reversible thermal expansion of the materials of construction is of significance, for some allowance for its accommodation must generally be made in the design; however, in most furnace structures it is generally found that about half the expansion of the actual bricks is taken up by the joints. The thermal expansion of the refractory is also an important factor in determining its resistance to thermal shock.

In general, the thermal expansion encountered in service tends to be less at temperatures above about 1,000° C. At high temperatures most refractories develop a certain amount of "give," owing to the softening of the bond; it follows that some of the expansion can be then taken up within the brick itself.

Firebricks have a low, fairly uniform expansion up to 1,000° C.; this is generally of the order of 0.5 per cent. or less. Silica bricks behave quite

differently. This has already been indicated in the section on constitution, but will be better appreciated from the diagrams in Figures 3 and 4.

It will be seen that tridymite shows two comparatively small irregularities, whereas cristobalite and quartz each show one large one. A normal silica brick

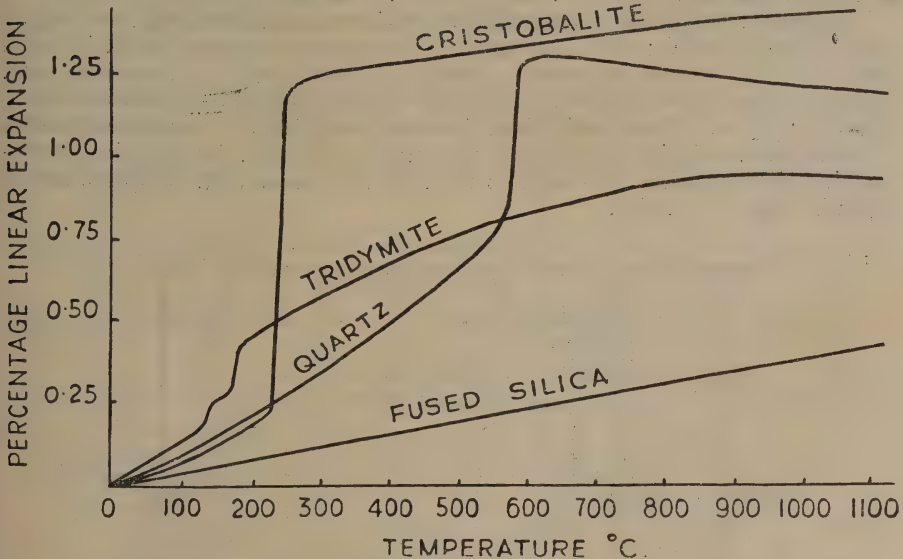


FIG. 3. Expansion of the silica minerals.

NOTE.—Recent research indicates that the curve for FUSED SILICA should be much more acutely inclined to the horizontal.

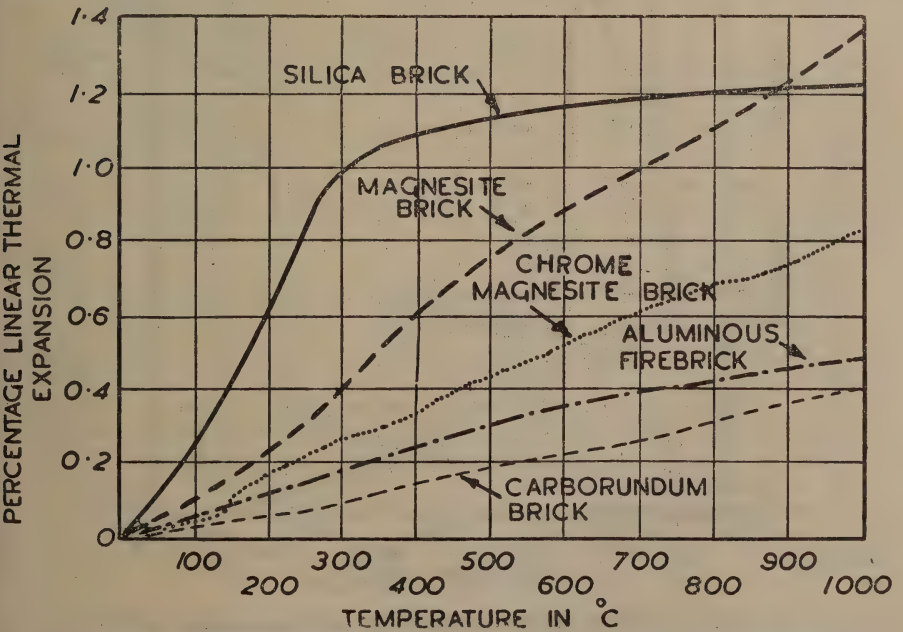


FIG. 4. Reversible linear expansion of several types of refractories.

NOTE.—The curve shown as for CARBORUNDUM BRICK relates to SILICON CARBIDE BRICK.

will show each of these discontinuities in its *thermal expansion curve* (Figure 6); careful examination of the curve for a silica brick or, better, of that relating the coefficient of expansion with temperature (Figure 5), will give a good indication of the constitution of the brick. The total thermal expansion of a silica brick between 0°C . and $1,000^{\circ}\text{C}$. is usually 1.2–1.25 per cent.

The thermal expansion of magnesite bricks is comparatively high, 1.3–1.4 per cent. up to $1,000^{\circ}\text{C}$.; that of a chrome or chrome-magnesite brick is much lower—(about 0.7–0.9 per cent.)—unless the atmosphere is a reducing one. Sillimanite has a low thermal expansion—approximately 0.5 per cent. up to $1,000^{\circ}\text{C}$.; that of silicon carbide is of the same order, but the thermal expansion of corundum bricks is higher (in the region of 1 per cent). Some typical curves showing the variation of reversible thermal expansion with temperature are given in Figs. 4, 6 and 7.

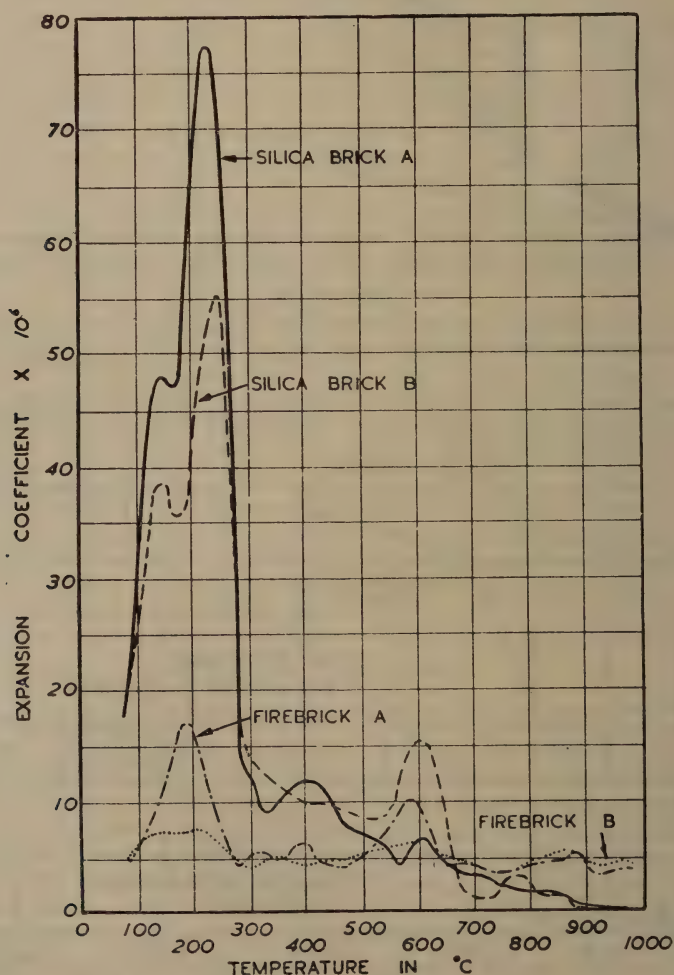


FIG. 5. Reversible thermal expansion of silica bricks and firebricks. The curves show how the coefficient of expansion varies with temperature.

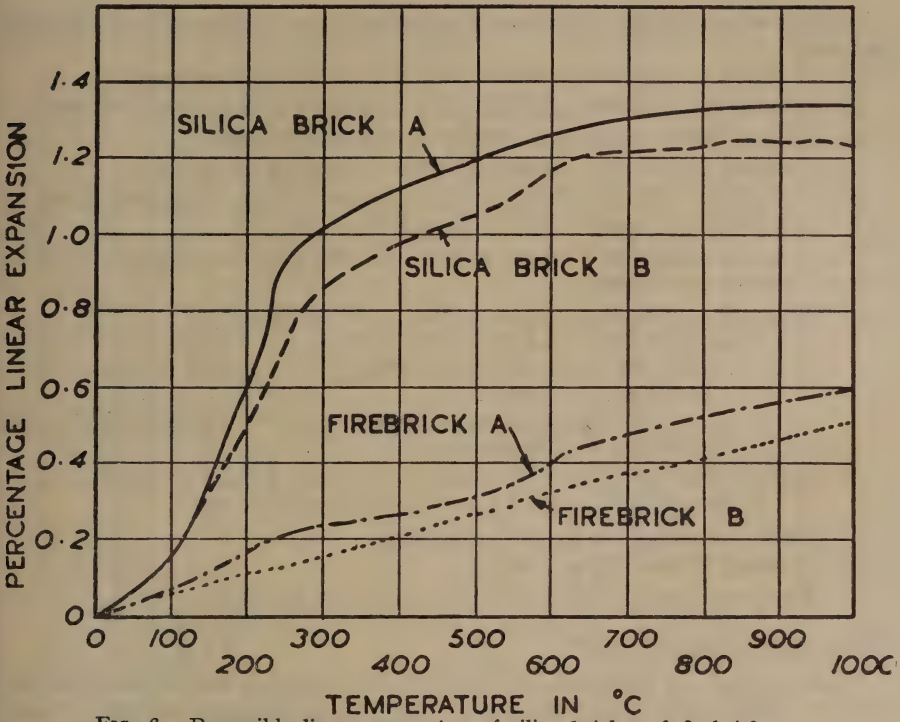


FIG. 6. Reversible linear expansion of silica brick and firebricks.

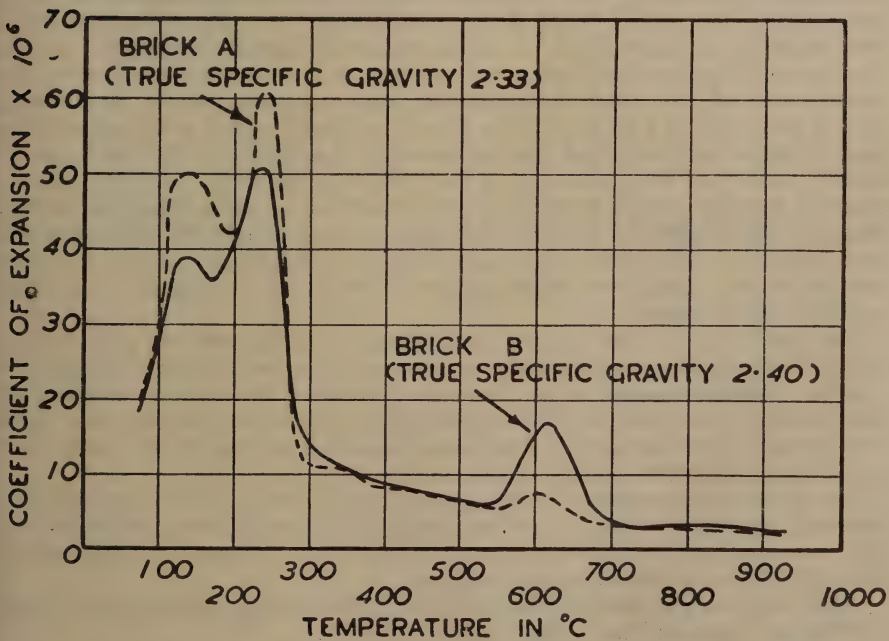


FIG. 7. Expansion of silica bricks. Brick A has been more strongly fired than brick B; its specific gravity has been reduced to an extent which shows that most of the original quartz has been converted, whereas Brick B still contains free quartz.

The following thermal properties of refractories are of interest to the furnace operator:

- (a) Thermal conductivity, influencing rate of heat transmission.
- (b) Specific heat, influencing quantity of heat stored in the brickwork.
- (c) Bulk density, which also influences the heat storage.
- (d) Thermal diffusivity, influencing rate of heating or cooling.
- (e) Emissivity, which influences the amount of heat radiated from, or absorbed by, furnace walls, roof and floor.

The units in which they are measured and the symbols generally used to denote them are as follows:

- (a) Thermal conductivity (k) = (i) B.t.u./ft² hr. deg.F./in.
or (ii) g. cal./cm.² sec. deg.C./cm.
to convert conductivity expressed as (ii) to that expressed as (i)
multiply by 2,900;
to convert conductivity expressed as (i) to that expressed as (ii)
multiply by 0.0003445.
- (b) Specific heat (s) in B.t.u. required to raise 1 lb. of brick through 1 deg.F.,
or calories to raise 1 gm. of brick through 1 deg.C.
- (c) Bulk density (ρ), in lb. per cubic foot.
- (d) Thermal diffusivity (a), = $k/s\rho$.
- (e) Emissivity, (ϵ), being a ratio, has no units.

THERMAL CONDUCTIVITY

The following is a discussion on the factors influencing the thermal conductivity of silica and fireclay products. Firstly, the generalisation may be made that the thermal conductivity of both firebricks and silica bricks increases with temperature. The precise value of the conductivity for either class of material depends on the texture, degree of firing and other factors, but since the rate of increase of conductivity with temperature is greater for silica bricks, the conductivity of this class of product at high temperatures, is, in general, greater than that of a firebrick. The thermal diffusivity of a well-burned silica product, however, is almost always greater than that of a firebrick, particularly at higher temperatures, a fact which appears to account for the effective thermal properties of silica refractories in the carbonising industries. Research has suggested that increasing the firing treatment increases the conductivity of both silica bricks and firebricks. This leads to the conclusion that under the influence of industrial usage the thermal conductivity of these products will increase.

The influence of porosity on the thermal conductivity of a refractory material has received considerable attention. A more porous brick has, in general, the lower conductivity. However, the size of the pores, in addition to their number, is a factor of importance. This is due to the fact that heat transfer can take place across the pores by radiation; this factor comes into particular prominence at high temperatures.

Not all refractories show a positive temperature coefficient of conductivity, however, two notable exceptions being magnesite and silicon carbide; corundum and zirconia refractories also probably have a negative temperature coefficient, but considerably less marked.

Some data on the thermal conductivity of refractories (taken mainly from "Technical Data on Fuel") are given in Table 7.

The data in Table 7 refer to the thermal conductivity at the temperatures stated. Data for the mean value of k over the temperature range 25° C. to t° C. (also mainly from "Technical Data on Fuel") are given in Table 8.

TABLE 7. THERMAL CONDUCTIVITY OF REFRACTORY MATERIALS

Characteristic	Material											
	Firebrick		Alumina brick	Silica brick		Zirconia brick	Zircon bricks		Mag- nesite brick: average	Silicon carbide bricks		
			81% Al ₂ O ₃	96% SiO ₂	93% SiO ₂	95% ZrO ₂	65% ZrO ₂ 30% SiO ₂	90% SiC		77% SiC	50% SiC	
Burning temp.—cone ..	10	14	15-16	16	16	—	—	15-6	—	15	10-11	10-11
do. °C. ..	1,300	1,410	1,450	1,460	1,460	—	—	1,450	—	1,435	1,310	1,310
Porosity—per. cent. ..	30	26.8	25.1	24.0	28.1	30	32.5	18.9	—	25.6	21.6	22.9
Conductivity—k B t.u./ft. ² hr.deg.F./in.												
at 300°C.	6-13	7-30	16-35	9-38	8-16	—	—	21.1	—	—	90	33
500°C.	6-76	7-76	15-32	10-12	9-02	6-0	12-2	17-35	24.9	108	80	32
700°C.	7-25	8-11	14-8	10-84	9-76	6-1	11-0	15-5	20-6	90	71	30
900°C.	7-50	8-31	14-53	11-58	10-43	6-1	10-2	14-2	17-4	77	63	28-5
1,100°C.	7-61	8-43	14-48	12-28	11-08	6-2	9-6	13-2	14-8	69	55	27

The conductivities of certain insulating bricks are given later. The character of the variation of the coefficient of thermal conductivity of firebrick, silica brick and diatomite insulating brick is illustrated in Fig. 8.

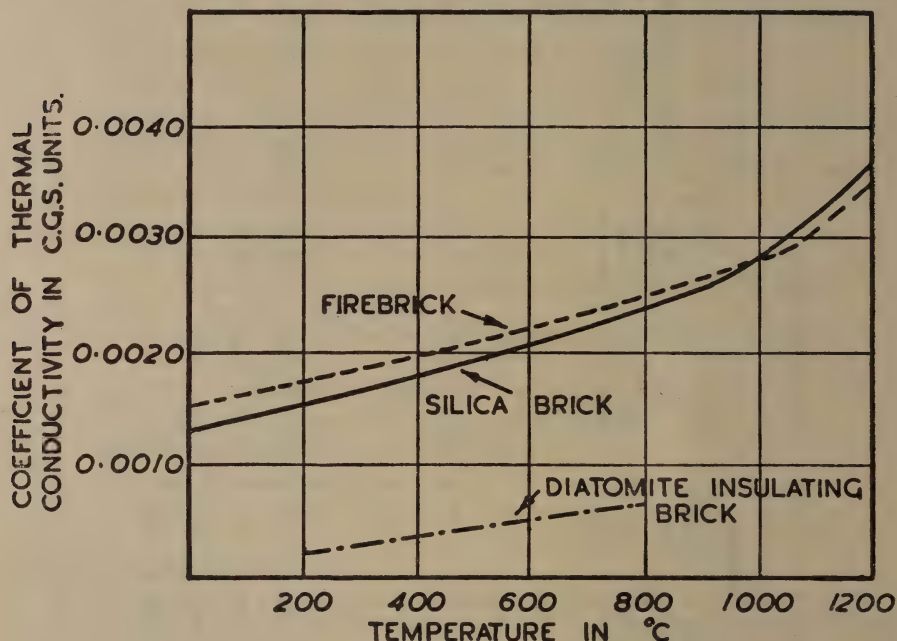


FIG. 8. Variation with temperature of the coefficient of thermal conductivity of firebrick, silica brick and insulating brick.

These curves represent typical values for each group of refractories, but considerable variations from the values shown may be found in individual samples.

Specific heat

Specific heat data are shown in Fig. 9. The specific heats of silica bricks and firebricks differ little; the values for magnesite and silicon carbide bricks are also similar.

TABLE 8. MEAN VALUES OF THERMAL CONDUCTIVITY BETWEEN 25° AND t° C. IN B.T.U. PER HR. PER SQ. FT. PER DEG. F. PER INCH THICKNESS*

Material	t =	100° C.	500° C.	1,000° C.
Corundum (fused Al_2O_3)		—	24 (between 650° C. and 1,250° C.)	—
Sillimanite brick	11	11	12	12
Silicon carbide brick	—	—	—	55-70
Chrome brick	12 ± 3	12 ± 3	12 ± 3	12 ± 3
Fireclay brick	4.5 ± 1.0	6.0 ± 1.0	8.0 ± 1.0	8.0 ± 1.0
Magnesite brick (electrically sintered)	—	40-45	—	—
Magnesite brick	45 ± 5	36 ± 5	28 ± 5	28 ± 5
Silica brick	6	8	10	10

*Values of the thermal conductivity, given in this form for convenience, are twelve times those for consistent units (per foot thickness).

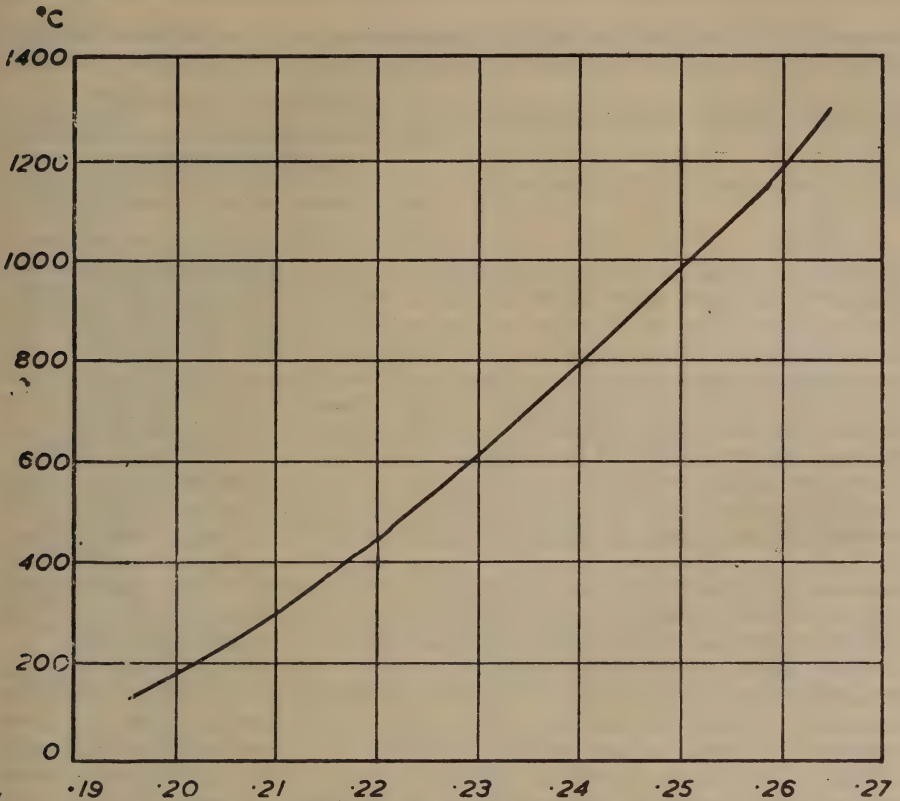


FIG. 9. Mean specific heat of a firebrick sample.
(S. T. Wilson and A. D. Holdcroft.)

MECHANICAL PROPERTIES

The mechanical properties of a refractory determined at room temperature must be used with extreme caution as a guide to the probable behaviour of the refractory at higher temperatures. However, a knowledge of the strength of a brick is useful as indicating its resistance to rough handling during transport, and in certain positions when abrasion resistance is important, at the top of a blast furnace stack for example, a brick of high crushing strength is usually sought.

With increasing temperature the mechanical properties of a refractory may either increase or decrease. In fireclay products, the crushing strength is generally found to increase with temperature up to about 1,000° C. when the bond starts to become viscous and the crushing strength becomes dependent on the duration of the stress. Thus at high temperatures a firebrick may withstand high loads for a short period, but may show subsidence under much lighter loads if they are maintained.

SPALLING

An important property of refractories in which the mechanical strength and elasticity have a considerable influence is the spalling resistance.

Thermal spalling, as distinct from physical and mechanical spalling, is caused by the development of stresses within the body of a brick consequent on changes in the temperature gradient. Calculation of the magnitude of these

stresses in the simplest case and their comparison with the ultimate strength of the material at the temperature in question, leads to the following formulæ:

On sudden heating: spalling tendency $\propto \frac{\text{Coefficient of expansion}}{\text{max. shearing strain} \times \sqrt{\text{diffusivity}}}$

On sudden cooling: spalling tendency $\propto \frac{\text{Coefficient of expansion}}{\text{max. tensile strain} \times \sqrt{\text{diffusivity}}}$

Examination of these formulæ shows that to resist spalling a brick should have a low coefficient of expansion, high strength and high thermal diffusivity. These requirements are fulfilled by silicon carbide, sillimanite and most firebricks. Silica bricks have a low spalling resistance below 600° C. owing to the high coefficient of expansion up to this temperature; above 600° C. the expansion becomes small and uniform and the spalling resistance increases. Magnesite bricks have a fairly high diffusivity and strength, but also have a high coefficient of expansion; in general, therefore, magnesite bricks fall between silica bricks and firebricks in their resistance to thermal shock.

A most important factor to be remembered is that almost without exception spalling is most liable to occur at comparatively low temperatures. At such temperatures the bond is glassy and will not yield to the expansion stresses; as the temperature rises, the bond becomes more deformable and will take up some of the stress. It follows that spalling occurs chiefly during the warming up and cooling down of furnaces; particular care must be taken during the warming and cooling of any furnace lined with silica or magnesite bricks.

Fully stabilized dolomite bricks should not be exposed to the furnace atmosphere, since with these products a peculiar type of spalling occurs on exposure to high temperatures. The sensitivity to thermal shock has been overcome to some extent by the production of a semi-stabilized dolomite brick. If a furnace is to be used intermittently, firebricks or sillimanite bricks are generally favoured because they will withstand repeated heating and cooling more successfully than most other of the commoner types of refractory.

THE ACTION OF SLAGS

It is probably unnecessary to emphasize the importance of the action of slags as a cause of refractory failure; it influences the refractories in at least 75 per cent. of industrial furnaces. The primary action of the slag is chemical solution of the brickwork, but ultimately physical disruption of the slagged surface may occur. If the slag is in motion, or if it is carried as small particles by flame gases, erosion will occur in addition to solution.

Whichever type of slag action predominates in a given furnace, the life of the lining will depend on the properties of the slag, the refractory, and the product of their interaction.

A most important factor is the fluidity and wetting power of the product of reaction. If a slag, though itself fluid at the temperature of operation, rapidly becomes viscous on taking brick into solution, then it may be expected that reaction will be slowed up, since further reaction can occur only by removal of, or diffusion through, the initial reacting layer. If, on the other hand, the product of reaction is itself fluid, reaction will, other things being equal, be more rapid. If it is assumed that the fluidity is related to the degree of superheat above the liquid temperature, the probable fluidity of the product of reaction of a slag and a refractory can often be estimated by a consideration of the appropriate equilibrium diagram. Examples of the low melting-point compounds frequently formed as products of reaction are given in Table 9.

TABLE 9

Composition	Fusion temperature °C.
Eutectics between lime and silica	1,400-1,455
Lime-alumina-silica eutectics:	
CaO, 23.3; Al ₂ O ₃ , 14.7; SiO ₂ , 62	1,170
CaO, 38; Al ₂ O ₃ , 20; SiO ₂ , 42	1,265
Lime-ferric oxide eutectic	1,203
Soda silica series: lowest eutectic	793
Ferrous oxide-silica series: eutectic	1,180
Ferrous oxide-alumina-silica series:	
Eutectic, FeO, 62; Al ₂ O ₃ , 3; SiO ₂ , 35	980
„ FeO, 68; Al ₂ O ₃ , 3; SiO ₂ , 29	1,002
„ FeO, 72; Al ₂ O ₃ , 3; SiO ₂ , 25	1,080

Coal ash is one of the most common corrodents of refractory materials. A typical ash consists of 24-25 per cent. SiO₂, 20-40 per cent. Al₂O₃, up to 30 per cent. Fe₂O₃, up to 10 per cent. CaO, up to 5 per cent. MgO, and 2-6 per cent. alkalis. Of the low-fusing constituents given in Table 9, compounds containing iron, lime and alkalis are most likely to arise from the action of coal ash.

Iron is particularly effective in promoting slagging under reducing conditions. The compounds of Fe₂O₃ with alumina and silica, in the absence of lime and alkalis, are not particularly fluid; when the Fe₂O₃ becomes reduced to FeO, however, as may occur in any furnace operating under reducing conditions, reaction becomes more rapid and the product of the reaction has a

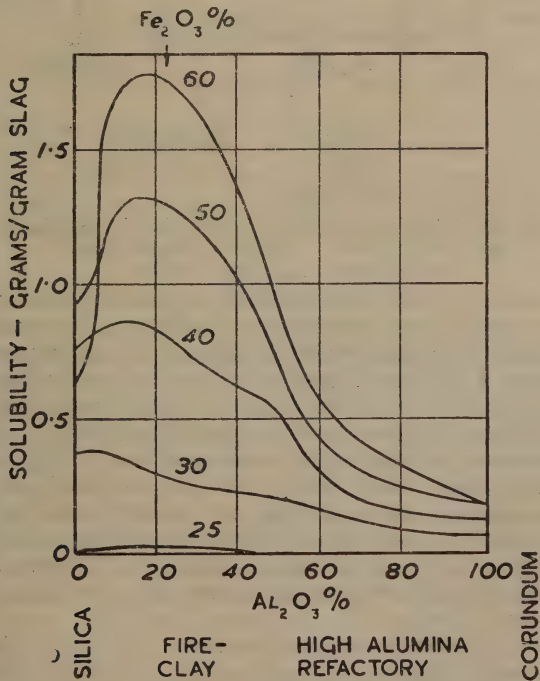


FIG. 10. Solubility of refractory materials in coal-slag.
Effect of iron oxide content.
(H. R. Fehling, *J. Inst. Fuel* XI 454).

low melting-point. A coal ash containing important amounts of both lime and iron oxide, may prove particularly destructive towards a furnace lining. A salty coal is also very reactive, as is well illustrated by the action of such coals on coke oven linings and gas retorts.

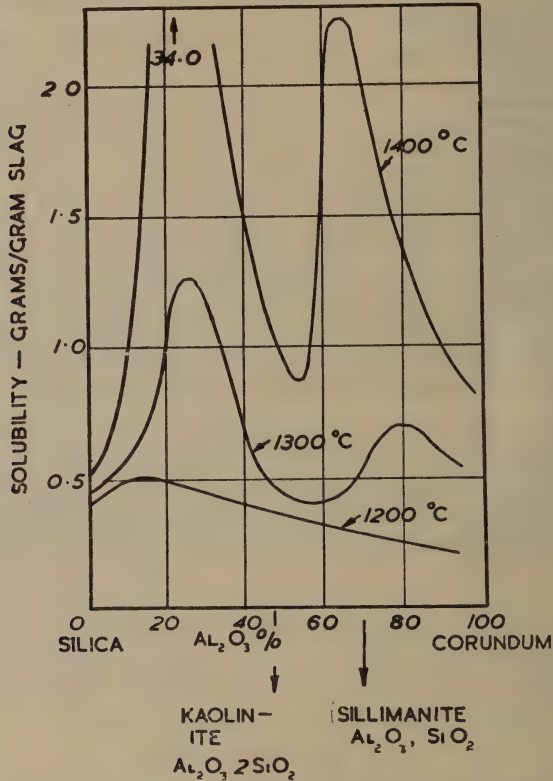


FIG. 11. Solubility of refractory materials in coal slag at 1,200°–1,400° C. Effect of temperature.
(H. R. Fehling, *J. Inst. Fuel*, XI, 454.)

The slagging action of iron compounds in a reducing atmosphere is illustrated in Figs. 10 and 11, which give the results of some experimental work¹.

These curves show the solubility of aluminosilicate refractory material in a coal ash between 1,200° and 1,400° C., the ash having the composition: 45–50 per cent. SiO₂, 30–35 per cent. Al₂O₃, 15–20 per cent. Fe₂O₃, 5 per cent. CaO plus MgO. Figure 10 shows the increase in solubility of firebrick in a coal ash as the iron oxide content of the ash increases. In Figure 11 it will be observed that rising temperature has a very great effect in accelerating the corrosive action, although the solubility curves have unusual features.

The effect of increasing temperature on the rate of slag attack is due to the decreased viscosity and to the increasing rate of all chemical reactions at high temperatures. The following figures have been published showing this effect in a coal ash:

Temperature (° C.) above softening point:	0	50	200
Viscosity (poises)	1,000	200	40
Velocity of flow (centimetres per hour)	5.2	8.9	15.3

Fig. 12 shows the effect on the softening temperature of mixing a limy slag with a good quality firebrick.

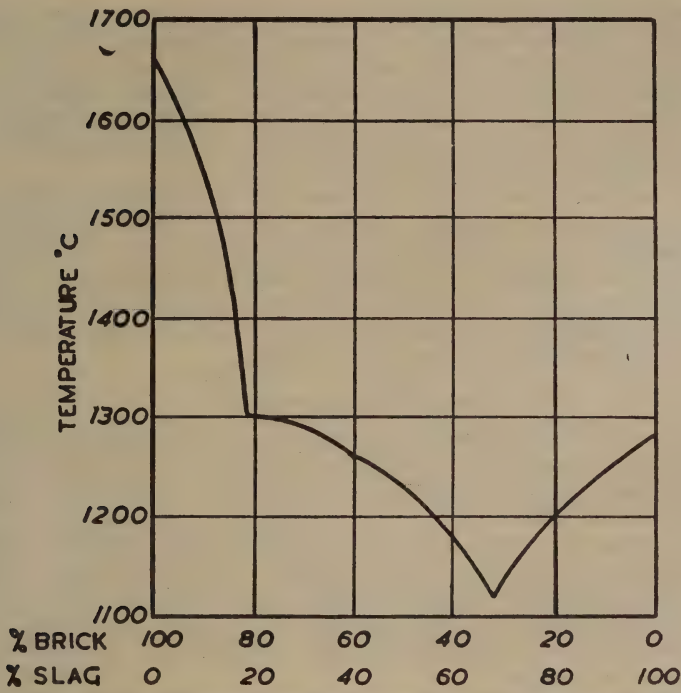
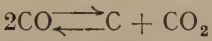


FIG. 12. Effect of a limy slag on the refractoriness (squatting temperature) of a fire-brick (33 per cent. alumina).

THE ACTION OF GASES AND VAPOURS

Several of the gases and vapours likely to be present in a furnace atmosphere are known to have a destructive action on the brickwork. Perhaps the best known instance of this is the effect of carbon monoxide on certain fireclay bricks. The reaction takes place at quite low temperatures (450°–550° C.), and is due to the breakdown of carbon monoxide into carbon and carbon dioxide, thus



This decomposition is facilitated by the presence of free iron oxide, so that if iron oxide is segregated in a brick, carbon deposition is liable to occur at the points of segregation. This carbon can disrupt the structure of the brick, and firebricks taken from the back of the shaft of a blast furnace, or from flues, are frequently found to be greyish in colour and cracked or friable.

Not all iron spots catalyse this reaction, and the proportion of iron oxide shown by chemical analysis is no criterion of the liability of the brick to disintegrate. Only uncombined iron oxide is active, and a decision as to the probable stability of a brick in an atmosphere containing carbon monoxide can be made only on the basis of laboratory tests.

It has been found that dilution of carbon monoxide by carbon dioxide, as is usual in flue gases, considerably reduces the disintegrating tendency.

Hydrocarbon gases, such as methane, also decompose to yield carbon when brought into contact with certain refractories, chiefly those of the fireclay type; with methane the maximum reactivity is found at 850°–900° C., but the temperature depends on the particular hydrocarbon and on the nature of the ferruginous matter in the brick.

The action of other gases is less well known. Water vapour has a damaging effect on basic refractories, and may also cause a reduction in the fusion temperature of firebricks and silica bricks; accordingly careful and thorough drying out of all newly-built furnaces should be a routine procedure. Chlorine may be present in small amounts in a furnace atmosphere as a result of decomposition of the salt frequently present in coal; chlorine will attack any iron compounds present in the furnace brickwork.

Alkalies, derived from the fuel or from the charge being heated, readily vaporize. In this form they can penetrate into the brickwork, and react to form compounds of low melting point; alkali attack may also give rise to a surface growth and peeling, a feature often observed in gas retorts, for example. Zinc, on the other hand, can vaporise and exert a physical action, since it may be deposited as metal in the pores and force the brick apart; this effect can sometimes be detected in the iron blast furnace.

JOINTING CEMENTS

It is generally acknowledged that in many high temperature installations, the cement joints exert a considerable influence on the ultimate durability of a furnace. Consequently the properties of jointing cements demand careful consideration and control.

There is a general consensus of opinion that the more important properties of refractory cements include the following: (1) refractoriness, (2) bonding strength, both dry and fired, (3) vitrification, (4) drying and firing shrinkages, (5) extent of reaction with the brickwork, (6) working properties, (7) screen size analysis, (8) chemical analysis, (9) coefficient of thermal expansion, (10) resistance to slagging.

Several of these properties are evidently inter-related. Thus the bonding strength must depend partly on reaction with the brickwork. Good bonding strength is desirable, but excessive reaction must be avoided. The bonding strength also depends in some measure on the working properties; if the water is immediately taken up from a cement when it is applied to a porous brick surface, there is less likelihood of the bond being firm than if the cement remains moist and can be worked into the surface pores when the next brick is placed in position. The drying and firing shrinkages are evidently of considerable importance; if they are excessive, the joint will crack. The incorporation of too much plastic clay in a jointing cement is likely to cause trouble in this direction, yet the workability must be adequate. The proportions of clay and grog must be carefully adjusted. The grading is also of importance.

The clay constituent of a fireclay/grog cement should pass a 36 B.S. sieve, in the interests both of thin joints and easy working; the grog constituent will normally be coarser, say through 16-mesh.

The chemical composition should in general be similar, but not necessarily identical, to that of the bricks; exceptions to this occur, e.g., in the use of chrome cements for purposes other than the jointing or patching of chrome and chrome-magnesite bricks. In silica cements, similarity should go beyond chemical composition to mineralogical constitution; the need for this will be appreciated when it is remembered that a fired silica brick, when converted to tridymite and cristobalite, will have expansion characteristics very different from those of a cement made up from unfired quartzite and/or sand. The addition of a proportion of crushed fired silica brick to a silica cement has been found to increase the bonding strength quite considerably.

INSULATING MATERIALS

The use of insulation to reduce heat transmission has been discussed in Chapter 9. The rate at which heat is lost from a vessel or structure depends

(other things being equal) upon the temperature of the exposed outer surface relative to the surroundings. Insulation is effected by providing a layer of material having a low heat conductivity between the internal hot surface of the vessel or furnace and the external surface, thus causing the temperature of the external surface to be materially reduced. As normally used, therefore, insulation reduces the escape of heat by keeping the outer surfaces cool. In refrigerating work, the insulation prevents the flow of heat from outside to the interior of the chamber.

The temperature to which the insulating material is raised in use is a matter of great importance. Insulating substances owe their property to a structure consisting of minute pores filled with air or gas which have in themselves a very low thermal conductivity. If the pores become partly filled up (as when the material becomes wet or compressed) or if the structure is disturbed (as when an insulating material settles into a solid block or is partly fused) the thermal conductivity is increased. Excessive heat affects all insulation adversely, but the temperatures to which the various insulating materials can be heated before this adverse effect occurs differ widely.

Clearly, therefore, the choice of an insulating material must depend upon the effectiveness with which it is required to operate and upon the temperature that it will withstand successfully.

It is usual to refer to the "insulation" of furnaces, and to the "lagging" of lower temperature plant such as steam pipes, because insulating material for furnaces is frequently used in the form of a brick, whilst for low temperature work it is more often applied as a plastic mass when the appliance is hot.

CLASSIFICATION

Insulators can be roughly divided into groups according to the temperature for which they can be used. A classification² is as follows:

(1) *Low Temperature Range*—below 90° C. (200° F.).

Refrigeration and building construction, including:

Refrigeration.

Transporters for ice, solid CO₂, ice cream, etc.

Cold storage.

Air conditioning.

Cool-water systems.

Hot-water systems.

Storage tanks.

Tank wagons.

Buildings.

The most commonly used materials are granulated cork, cork board, wood (ordinary and special), wood pulp, pulp boards, straw boards, grasses, charcoal, sponge rubber, mineral fibres, aluminium foil.

(2) *Medium Temperature Range*—90°–375° C. (200°–700° F.).

Power station practice, steam raising and low temperature heating, including:

Boilers.

Steam lines.

Steam accumulators.

Hot-air systems.

Drying plant.

Flue gas ducting.

Turbines.

Cylinders.

Tank wagons.

Those most used are 85 per cent. magnesia-asbestos, other magnesia compositions, diatomaceous compositions, slag wool, spun glass, felted asbestos, bonded asbestos, asbestos mattresses, asbestos paper and mill-board in various manufactured forms, aluminium foil, other metal foils and sheets.

(3) *Moderately High Temperature Range*—325°–650° C. (600°–1,200° F.)

Typical uses are superheated steam plant, ovens, stoves and diesel engine exhausts. Here the choice is more limited, being restricted to asbestos—up to 450° C. (850° F.), spun glass—up to 480° C. (900° F.), diatomite, asbestos compositions, magnesia-diatomite-asbestos compositions, aluminium foil.

(4) *High Temperature Range*—600° C. (1,100° F.) upwards.

Insulation for the highest temperature ranges applies generally to industrial furnace practice and carbonisation, typical applications being kilns, heat-treating furnaces, gas-retort settings, regenerative stoves, hot-blast mains, gas producers and coke ovens.

The choice of material is restricted generally to refractory insulating materials. These are of three general types—products made from diatomaceous earth and from vermiculite and the type known as *hot-face insulation*, usually made from a refractory base such as fireclay or silica. Hot-face insulating materials, which are also referred to as *insulating refractories*, are used for the inside linings of furnaces, being more robust and refractory than diatomite or vermiculite, although having a somewhat lower insulating value.

CONDUCTIVITY

Table 10, giving the thermal conductivity characteristics of some insulating materials, should be taken as a general guide only, as different specimens of the same material may show differences in thermal conductivity.

TABLE 10. THERMAL CONDUCTIVITIES OF SOME INSULATING MATERIALS

<i>Material</i>	0° C.	100° C.	400° C.	600° C.
Asbestos	1.05	1.35	1.50	1.65
Asbestos felt	—	0.45	0.65	—
Balsa wood	0.35	—	—	—
Charcoal	0.35	—	—	—
Cork, granulated	0.30	—	—	—
Cork, slab	0.32	—	—	—
Cotton wool	0.30	—	—	—
Diatomaceous earth	0.40–0.55	0.50–0.60	0.60–0.70	0.7–1.0
85 per cent. magnesia	—	0.42	0.58	—
Spun glass	—	0.45	0.65	—
Expanded rubber	—	0.2–0.25	—	—
Rubber sponge	0.38	—	—	—
White dry sand	—	2.5	—	—
Sawdust	0.35	—	—	—
Hair felt	—	0.25–0.35	—	—
Yellow pine	—	1.1–1.15	—	—
Slag wool	0.29	0.35	—	1.33
Wool	2.6	—	—	—
Pipe coverings:				
Plastic magnesia	—	0.40	0.64	0.92
Plastic asbestos	—	0.67	0.87	—
Glass fibre mattresses	—	0.33	0.7	—
Heavy materials	—	1.15	1.28	1.36

Insulating bricks over the mean range 0° C. to:

	200° C.	400° C.	600° C.	800° C.
Insulating refractories	1.74	1.89	2.03	2.18
Diatomaceous bricks (porous grade)	0.73	0.81	0.90	1.02
Diatomaceous bricks (solid grade)	1.07	1.20	1.36	1.45
Vermiculite bricks (27 lb./cu. ft.)	1.03	1.20	1.38	1.54

Conductivity (k) expressed as B.t.u./sq. ft. hr. deg. F. per inch thickness.

INSULATING REFRACTORIES

When insulation is placed behind the refractory lining of a high temperature furnace, the interfacial temperature may rise above the value permissible for normal insulating materials. (See Chapter 19.) The best procedure is to use *insulating refractories*. Two methods of insulation are favoured. When the furnace is operating continuously, or where the conditions of temperature and atmosphere are very severe, a lagging of diatomaceous insulation is placed behind a dense refractory face; in other installations where cleaner conditions or a lower temperature permit, and particularly in short-cycle intermittent furnaces and kilns, the insulating material can itself form the refractory lining, no insulating refractory being used. Materials of the latter type are highly porous and refractory and have fair strength and spalling resistance; they can, in general, be used up to a temperature above $1,300^{\circ}\text{C}.$; some recently developed special insulating refractories can be used at a hot-face temperature of $1,500^{\circ}\text{C}.$

Most insulating refractories consist of fireclay, the high porosity being attained by the incorporation of a combustible material, e.g. sawdust, in the raw mix; other methods, such as forming of a clay slip, are available but are difficult to control under full-scale manufacturing conditions.

Table 11 gives typical figures for two grades of high temperature insulating material, with those for a firebrick for comparison.

TABLE 11
CONDUCTIVITIES (k) FOR TWO GRADES OF HIGH TEMPERATURE
INSULATING MATERIAL

(The mean temperature is taken as the arithmetic mean between the hot and cool face temperatures.)

Mean temp. $^{\circ}\text{F}.$	Insulating brick "A"	Insulating refractory "B"	Firebrick
300	0.84	—	6.23
500	1.02	1.64	6.69
600	1.085	1.75	6.92
700	1.14	1.86	7.15
800	1.18	1.94	7.38
900	1.20	2.03	7.61
1,000	1.22	2.11	7.84
1,100	1.23	2.18	8.07
1,200	1.24	2.24	8.30
1,300	1.25	2.30	8.53
1,400	1.26	2.36	8.76
1,500	—	2.41	8.99
1,600	—	2.46	9.22
Max. temp. at which material can be used:			
$^{\circ}\text{C}.$	870	1,250	—
$^{\circ}\text{F}.$	1,600	2,280	—

$k = \text{B.t.u./sq. ft. hr. deg. F./in.}$

The effect of using these bricks is shown in Fig. 13. Fig. 13 (A) shows the temperature gradient in a refractory wall of silica brick $13\frac{1}{2}$ inches thick backed by $4\frac{1}{2}$ inches of red brick. In Fig 13 (B) $4\frac{1}{2}$ inch of Grade A brick has been interposed between the red brick and the refractory. It will be seen that the interfacial temperature is higher than that which the diatomaceous insulation will withstand. In Fig. 13 (C) there is the same arrangement as in Fig. 13 (B) but the Grade A brick has been replaced by Grade B brick. The

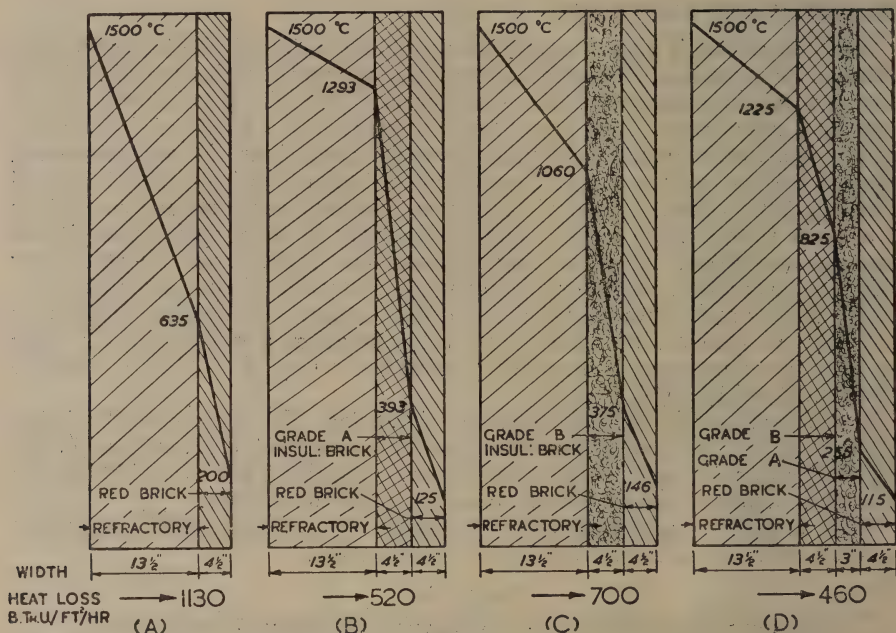


FIG. 13. The use of insulating materials.

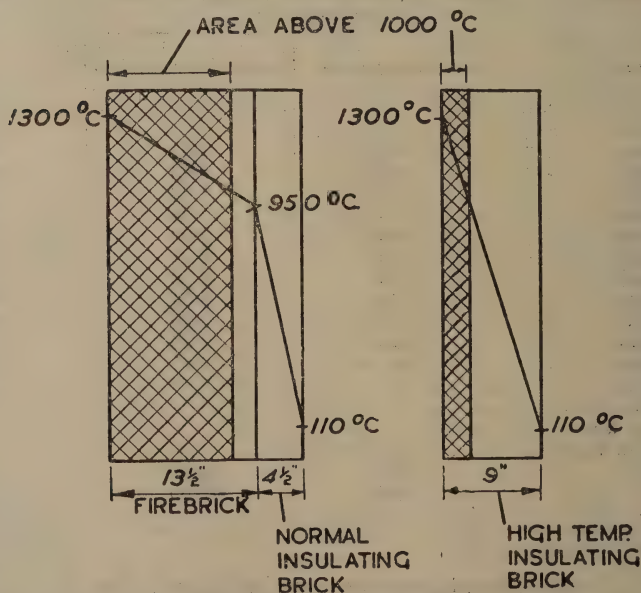


FIG. 14. The thermal effect of hot face insulation.

result is not so satisfactory in lowering the temperature of the outer surface, but no part of the structure is overheated. Finally, in Fig. 13 (D) the insulating layer is divided into two parts, 4½ inches of Grade B brick and 3 inches of Grade A; here the structure is sound and heat conservation is satisfactory.

The insulating refractory increases the uniformity of temperature in a furnace for three reasons;

- (i) the heat radiation is high because of the high surface temperature;
- (ii) the temperature drop along the path taken by the gases is proportional to the heat losses from the furnace walls; by reducing the heat loss the temperature drop is reduced;
- (iii) the flow of heat parallel to the wall face and towards doors and other openings is reduced.

Hot-face insulating bricks are lighter than normal refractories, weighing perhaps only one-third to one-half as much. Moreover, the heat penetration into the brick is less, and the use of these bricks results in much less heat storage in the furnace walls. (See Chapter 19.)

This feature of insulating refractories is illustrated in Fig. 14. The shaded portion shows the extent to which the temperature of the material of the wall is above $1,000^{\circ}\text{C}$. The weight of the wall for the full thickness shown, per square foot of superficial area, would be 150 lb. for the composite wall and 30 lb. for the wall of high temperature insulating brick. The heat stored by the two walls, per square foot of superficial area would be approximately 75,000 B.t.u. and 9,000 B.t.u. respectively. The surface temperature is the same for the two walls, so that the external surface heat losses would be the same in the two instances. This comparison indicates the features of the new technique of hot-face insulation which has been a most important contribution to greater furnace efficiency.

An important limitation of insulating refractories is their poor resistance to slags. The external structure, being highly porous, is readily penetrated and dissolved by fluid slag and although coatings have been tried, they have been only partly successful, and in general these bricks can be used only under clean heat conditions.

A second limitation is the rather low resistance to abrasion which prevents these bricks from being used as a working hearth. For the same reason they cannot be recommended for positions where they will be scoured by dust-laden gases at high velocity, unless they are coated with a denser material. The resistance to heavy mechanical vibration is not so high as with firebrick, and in forging furnaces adjacent to heavy hammers, for example, it is advisable to use heavier and more rugged constructional materials.

LAGGING

The fundamental requirements of a lagging are:

- (a) The thermal conductivity must be low.
- (b) It must be capable of adhering to the surface to which it is applied.
- (c) When applied it must have a reasonable resistance to the weather, and to other agents causing deterioration.
- (d) When required to operate intermittently, i.e., when the vessel is heated and cooled at frequent intervals, it should have a low heat storage capacity.

The value of a lagging material can be assessed only after it has been applied. Comparisons between samples in the raw state are useless because the treatment required in practice to apply these laggings may appreciably modify their conductivities.

Great care must be taken in installing the lagging in place since much of its value can be destroyed by improper installation. Clearly the first cost of the lagging material is not the sole criterion when considering the economic aspect; the cost of the labour required to apply the lagging to the hot surface must be taken into account and this is usually appreciable and may vary for different

laggings. Neither does it follow that the lagging material which has the lowest thermal conductivity as received will necessarily be the most efficient lagging when applied.

It is always advisable to obtain detailed instructions of the method of application of a particular lagging from the makers. Many factors can influence the heat-saving properties of a lagging and once it has been installed it should not be subjected to rough handling or other mechanical damage. A low-grade composition, however low its installation cost, is not generally economical for high temperature insulation, and should not be used except as a temporary expedient.

Protection of Lagging

Special care must be exercised in protecting lagging from the effects of moisture and mechanical damage. From their general nature laggings are porous, and consequently readily absorb moisture which greatly reduces their efficiency. In extreme conditions the heat loss arising from this cause may amount to ten times its value with dry lagging.

The cheapest method of protecting lagging is to wrap roof felting round it and to secure this with single strands of wire. There are several more expensive methods of protection, which seal the lagging from the atmosphere and at the same time provide it with a more adequate protection against mechanical damage. These are usually compounds of a bituminous nature.

PROPERTIES OF TYPICAL LAGGING MATERIALS

Slag Wool. This is a good heat insulator, and is comparatively cheap, but special care must be taken when installing it. It can be applied to hot surfaces having temperatures up to 600° C.

It is usually supplied by the makers in the form of a mattress 3 feet long. The width is such that it can just be wrapped once round the pipe. When the required thickness of the lagging is more than 2 inches, it is advisable to obtain this thickness by installing two layers of mattresses.

The mattresses are secured in position by tightly winding a wire round them. For pipes of less than 1 foot diameter, the distance between each turn of the wire should be of the order of 2 inches, but for larger pipes it is necessary to space the wire more closely. Care should be taken to ensure that the mattress is protected against moisture and mechanical damage, and that there are no large air spaces between it and the pipe. It is very important that a high grade of slag wool, free from impurities, should be used.

Magnesia. The cost of magnesia lagging is approximately the same as that of slag wool, but the installation is probably easier for large vessels and somewhat more difficult for small pipes. It is more rigid than slag wool, but should not be used on surfaces at a greater temperature than 300° C. This disadvantage can be overcome by interposing a thin layer of special cement between the magnesia and the hot surface. Magnesia lagging is obtained in the form of slabs, which are laid along the pipe and secured temporarily with strands of wire. A hard-setting cement-like compound is then applied to the outside, in order to secure the slabs permanently, and to fill the gaps between adjacent slabs.

Glass Wool. At temperatures below about 300° C. glass wool has a greater thermal resistance than slag wool or magnesia. It is more expensive and cannot be used for temperatures above 500° C.

It is obtained in the form of mattresses which can be secured in the same manner as slag wool, or in the form of rigid semi-circular sections, specially moulded to fit the pipe, which can be secured with metal bands.

Asbestos. There are many different types of asbestos used for lagging purposes, and consequently the available range of temperature varies widely. The cheaper types of asbestos usually have a higher thermal conductivity than either slag wool or magnesia and many of them are liable to absorb water. Furthermore, there are certain types of asbestos which can only be used for lagging at relatively low temperatures (of the order of 150°–250° C.). There are, however, grades of asbestos which can be used for higher temperatures (up to 600° C.).

Asbestos lagging is usually manufactured in the form of rigid semi-circular sections, specially moulded to fit the surface to which they can be secured with metal bands.

Temporary Lagging. Straw and felt are probably the cheapest lagging materials available and are useful when a temporary lagging is required. They can be wrapped round a pipe and secured with single strands of wire or string. They should not be used for a surface hotter than 200° C. Exposure to the weather is likely to destroy their insulating properties.

LAGGING OF PIPES

Because of the comparatively low temperature met with in hot water central heating plants, it is too often erroneously assumed that lagging of pipe-work and vessels conveying or storing the heated water is not important. It is true, of course, that the higher the temperature the greater the loss from unlagged pipes, but even with comparatively low temperature systems normally used for central heating, lagging of pipes and boilers is an exceedingly good investment.

The economies of insulation for these lower temperatures can be shown by considering an installation comprising small pipes of 1 inch diameter, conveying hot water at an average temperature of 140° F. over 625 feet in total length, the surrounding air being at 65° F. If a lagging is used consisting of 85 per cent. magnesia of stated thickness, plus $\frac{1}{2}$ inch of hard-setting composition, it will achieve a saving of 25,000 B.t.u. per hour.

Heat Saving by Lagging Steam Pipes.

The magnitude of the losses that can take place from steam pipes may be indicated by an example. If a 1-inch steam pipe having a surface temperature of 200° C. is unlagged for a length of 200 feet, it may waste 9 lb. of coal in an hour or 35 tons a year. If the same piping had a surface temperature of 360° C. (680° F.) about 105 tons of coal would be wasted. As the temperature of a surface rises so the heat loss increases; consequently the thickness of lagging or the efficiency of the insulation must be stepped up correspondingly.

It follows, therefore, that even if a pipe is lagged it cannot be assumed to be efficiently lagged. Many hot surfaces that are lagged are inadequately insulated and some preventable loss is occurring. Some indication of the thickness of lagging required at different temperatures and the heat saved by lagging is given in Table 12.

For boiler and steam work generally all hot surfaces should be lagged. This applies to valves, flanges, etc., as well as to straight runs of pipe, boiler fronts, storage tanks and so forth. Boiler settings should be insulated. Ancillary apparatus, valves, dampers, etc., should be so placed that there is no need to walk upon the insulation, e.g., upon the boiler tops, to reach them.

SELECTION AND TESTING OF REFRACTORY MATERIALS

Correct selection of refractory materials can be made only on the basis of a full knowledge of the conditions of service and of the properties of the available refractories. These properties can be evaluated fairly accurately in the laboratory. The testing methods that should be used have been standardized.³

TABLE 12. EFFECT OF THICKNESS OF LAGGING ON HEAT LOSS FROM STEAM PIPES

Diam. of main	Temp. of Surface to be lagged		Thickness of lagging	Heat loss per ft. length—B.t.u./hr.		Efficiency of lagging	Heat lost per sq. ft.: B.t.u./hr.	
	° C.	° F.		Unlagged	Lagged		Unlagged	Lagged
4 in.	80	176	1½	275	65	76.4	233	55
	160	320	2	885	126	85.7	750	107
	240	464	2¼	1,860	179	88.9	1,576	152
	320	608	2½	3,230	207	92.5	2,740	182
	400	752	3	5,220	282	94.4	4,420	240
8 in.	80	176	1½	520	110	79.0	233	50
	160	320	2	1,670	210	87.4	750	95
	240	464	2¼	3,500	300	91.5	1,576	135
	320	608	2½	6,100	392	93.5	2,740	177
	400	752	3	9,800	440	95.6	4,420	198

They consist of special chemical analysis and the determination of: true specific gravity, true and apparent porosity, bulk density, permeability, refractoriness, refractoriness-under-load, permanent linear change on reheating, cold crushing strength, reversible thermal expansion, and resistance to carbon monoxide. The importance of paying adequate attention to proper sampling cannot be too strongly stressed.

Testing methods are also available for determining spalling resistance, thermal conductivity and specific heat; but standard methods have not yet been prescribed. Examination of a refractory material by the microscope and by X-ray methods may give valuable information regarding its constitution.

It is not necessary to do all these tests on any one brand of brick, but no one test will by itself give all the information required. In testing a firebrick, for example, attention should be paid more particularly to chemical composition, refractoriness, refractoriness-under-load, porosity and after-contraction; if the firebrick is for use in the shaft of a blast furnace, resistance to carbon monoxide, and crushing strength should be determined. Where a brick is to be exposed to slags or noxious gases, information as to its permeability is useful.

A somewhat different series of tests would probably be used before selecting a silica brick. Micro-examination and determination of true specific gravity are essential, since the mineralogical constitution is of more importance than the chemical composition. Chemical analysis can usually be omitted unless the brick is to be used under very severe temperature conditions, in which case determination of the alumina and alkalis is important. Refractoriness-under-load gives a useful check on quality. After-expansion should be determined if the brick contains much quartz—as seen by the microscope, or indicated by a high specific gravity. Reversible thermal expansion also gives useful information on the constitution of silica refractories.

In selecting basic refractories, it is useful to know the chemical composition. For a magnesite or dolomite brick further tests should be refractoriness-under-load, after-contraction, porosity and spalling resistance; ordinary refractoriness of these products is always above 1,800° C. and need not be determined. A chrome or chrome-magnesite brick should be tested in a manner similar to that for a magnesite product, but a further test should be added, viz. determination of the bursting expansion when heated in contact with iron oxide.

Turning to the definition of the service conditions, it is well known by all who are associated with the operation of any furnace that many factors may

influence the life of the lining. In many cases, a variation of these conditions, frequently accidental, may have a greater influence on the service obtained from the bricks than any variation in the properties of the bricks themselves. Some of the factors which should be considered are: the maximum temperature; the load, especially the thrust in arches; the nature of the slag, ash or gases; the possibility of rapid temperature fluctuations; the necessity or otherwise for resistance to abrasion or impact; the thermal properties and the standard of the building technique in particular in regard to the character of the joints and the jointing material.

A knowledge of these conditions, an appreciation of the general technology of refractory materials, and test data on available products, will serve as a foundation for scientific selection and ultimate economy both in refractories and fuel consumption.

As a general statement on selection, it may be noted that, in the sphere of fireclay products, the more aluminous materials are the more refractory, and, as a result of their chemical nature, are less reactive towards certain types of slag. Siliceous firebricks containing 78–92 per cent. SiO_2 , on the other hand, show considerable volume stability at temperatures up to $1,350^\circ\text{C}$., or even higher, and, on this account, have a sphere of use in the carbonising and other industries. Silica bricks, characterised by high strength at elevated temperatures, are widely used in the arches of furnaces operating under severe conditions. However, the tendency of silica bricks to spall at low temperatures must be kept in mind when selecting this type of refractory for a particular usage; since the abrupt expansion of silica occurs only at low temperatures, furnaces lined with this material may be subjected to wide temperature fluctuations above 600°C . without damage.

In positions demanding mechanical strength at high temperatures, but in which the slagging conditions preclude the use of silica, sillimanite refractories find a specialised use; they are widely employed in the glass industry.

Basic refractories, among which may be included magnesite, chrome-magnesite and dolomite bricks, are used chiefly in the metallurgical industries. In basic steel making furnaces, for example, magnesite or dolomite bricks are used as a hearth lining and chrome and magnesite have found increasing use in the walls and ports. Some steel furnaces have been built with chrome-magnesite roofs.

CONSTRUCTIONAL ASPECTS

METHODS OF BUILDING REFRACTORY STRUCTURES

Furnace bricklaying is a trade in itself and should be entrusted to those accustomed to the behaviour of brickwork under furnace conditions. Brickwork is essentially a mass made up of small individual units, and the method of placing these units and their relative position one to another are of considerable importance to the stability of the structure. The bricks are generally laid in a series of horizontal courses, and the problem is to find the best bond for the particular thickness of wall and the furnace conditions.

For ordinary work the standard size brick is $9 \times 4\frac{1}{2} \times 3$ inches, and the methods of bonding given below are based on that unit. The use of smaller bricks, e.g. $9 \times 4\frac{1}{2} \times 2\frac{1}{2}$ inches, increases the cost per cubic yard and also the cost of the bricklaying.

Stretcher Bond. This is applicable only to a $4\frac{1}{2}$ -inch wall, and is used mainly in small furnace construction (Fig. 15).

Header Bond. This gives perfect bonding in a 9-inch wall, and is the best general arrangement for high temperatures, especially if the load on the brickwork is high; the load can be carried by the cooler ends of the brick where the

temperature is lower (Fig. 16). For walls thicker than 9 inches the combination of some stretcher courses with the headers is necessary to get a tie or bond throughout the thickness of the wall. The advantages of a header bond can still be retained in a $13\frac{1}{2}$ inch wall by using $9 \times 4\frac{1}{2} \times 3$ -inch headers on the hot face and $13\frac{1}{2} \times 4\frac{1}{2} \times 3$ -inch headers every third or fourth course as a tie. Alternatively, header bond can be used entirely for a $13\frac{1}{2}$ -inch wall by using $13\frac{1}{2} \times 6 \times 3$ -inch bricks.

English Bond. Alternate courses of headers and stretchers (Fig. 17). This is the most common bond for $13\frac{1}{2}$ -inch walls, and is also used for thicker walls. It is necessary to use a soap or pup brick, $9 \times 3 \times 2\frac{1}{4}$ inches, in starting off certain courses to get the correct bond. The use of soaps eliminates cutting.

A common variation of the English bond is to have two or three header courses on the hot face and one stretcher (Fig. 18), and for most furnace work this is better than alternate header and stretcher.

Dutch Bond. This is similar to English bond (Fig. 19), but gives even better bonding. The alternate stretcher courses are not coincident and this makes it less likely to have several vertical joints coinciding in a long wall where the bricks may gradually run out of the bond.

Arches. Firebrick arches are usually bonded (Fig. 20). For building 9-inch arches where the conditions are severe and the end of the arch is exposed, as in the stoker arches of water-tube boilers, the use of a special bonder brick, $9 \times 6\frac{3}{4} \times 3$ inches, for breaking bond eliminates small cut bricks and gives a much stronger arch.

In firebrick arches up to 12 inches thick, one course is usually employed, but for an 18-inch arch, two rings of 9-inch bricks are more satisfactory.

Arches constructed of silica bricks are more often built in rings (Fig. 21). The thermal expansion of silica bricks is considerably greater than that of firebricks, and most of it occurs suddenly at a low temperature, below 300°C . The building in separate rings may give greater flexibility in providing for the thermal expansion of the heating up of a large furnace; this method of arch construction also makes greater allowance for small deviations from the standard size of individual bricks.

Silica arches are often built dry, without the use of jointing cement. When an arch is built dry the bricks should fit closely, otherwise stresses are set up which may cause cracking. It is advisable to adopt the ring construction to ensure the closest contact between the bricks.

Circular Walls. For building shaft furnaces, e.g. blast furnaces, lime kilns, etc., where conditions are severe and the thickness of the lining is considerable, improved bond is obtained by the adoption of $13\frac{1}{2}$ inch bricks in addition to 9 inches, and the width of the bricks is then 6 inches instead of $4\frac{1}{2}$ inches. The usual methods of bonding are shown in Fig. 22.

Allowance for Expansion. Experience has shown that in brickwork the individual bricks do not slide over each other, but that the wall expands in mass as a single unit. It is now customary to leave clear spaces for expansion instead of inserting cardboard or wood as was formerly done. Roughly speaking, in practice, the theoretical allowance required is as follows, but it is often found that up to half of the expansion of the brickwork is taken up by the joints:

95 per cent. silica—1.25 per cent. linear (3 inches on a 20-foot wall).

Firebricks—0.75 per cent. linear (1.8 inch on a 20-foot wall).

With silica bricks, the bulk of the expansion takes place at a temperature before the wood has had an opportunity to burn out. Thermal expansion must take place, and, if suitable provision is not made for it, enormous stresses are built up and serious damage may result.

Joints should always be kept as thin as possible no matter what method of bonding is adopted.

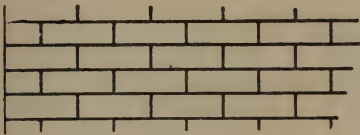


FIG. 15. Stretcher bond.

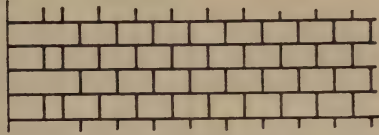


FIG. 16. Header bond.



FIG. 17. English bond.



FIG. 18. Modified English bond.



FIG. 19. Dutch bond.

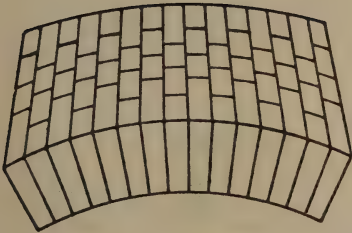


FIG. 20. Bonded arch.

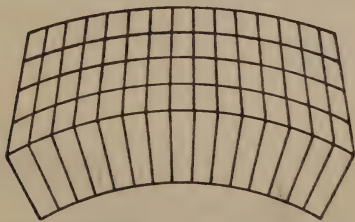
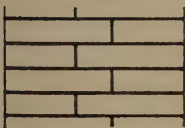
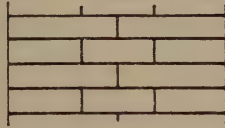


FIG. 21. Ring arch.



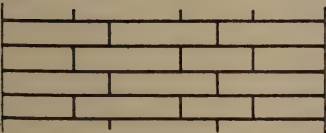
22 1/2-inch wall.



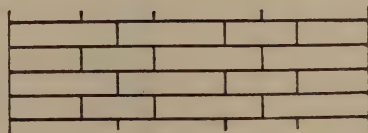
27-inch wall.



31 1/2-inch wall.



40 1/2-inch wall.



45-inch wall.

FIG. 22. Methods of bonding walls of various thicknesses.

FIGS. 15-22. Methods of bonding bricks.

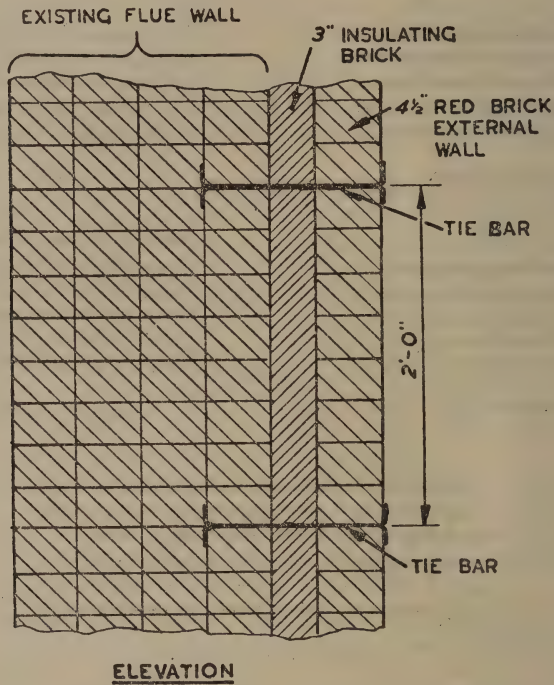


FIG. 23. Method of attaching insulation to an existing flue wall.

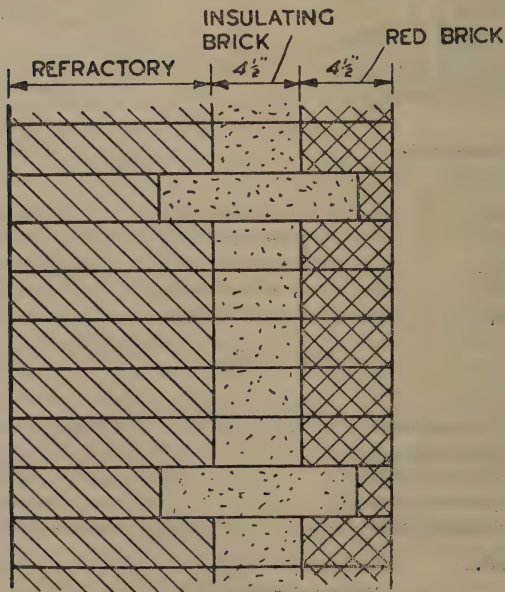


FIG. 24. Method of incorporating insulation during building.

CONSTRUCTION OF INSULATING WALLS

Insulation of existing high temperature furnaces, as has been indicated previously in Chapter 19, should be undertaken only with expert advice on account of the increased temperature occasioned in the brickwork on the furnace, or hot, side.

Existing lower temperature furnaces, including boiler settings, can be insulated by the method shown in Fig. 23. A $4\frac{1}{2}$ -inch brick wall is built outside the existing one, leaving a suitable gap, 3 inches or $4\frac{1}{2}$ inches between the old and the new walls in which the insulating bricks can be inserted as the wall is built. To keep the outside wall rigid, it is necessary to incorporate one or two buttresses, and further strength can be obtained by fixing a number of T-bars about 2 feet apart, as shown in Fig. 23. After the insulating slabs are fixed, periodical pointing of the external brickwork will be found necessary.

In new installations, insulating bricks should be built in the side walls and protected on the outside by red brick. One method of building a composite wall of this character is shown in Fig. 24. The tops of flues should also be covered with insulating bricks in the form of slabs $12 \times 12 \times 3$ inches. It is advisable to protect insulation from mechanical damage.

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The reader is also referred to the papers published by the Institute of Fuel (*J.* **18**, **19**, 1944-1946) and the Progress Review on Refractories, 1950-1953 (*J.* 1953, **26**).

See also the section on Refractories in "Technical Data on Fuel".

CHAPTER 24

SPACE HEATING

INTRODUCTION

BUILDINGS are heated to provide suitable conditions of warmth for the comfort of the occupants, or suitable temperatures for industrial processes. The appropriate temperature is not the same for all classes of buildings, but depends upon the nature and purpose of the building. Whatever the building, however, it is important, as regards fuel economy, that the temperature should not be higher than necessary, as a rise of only 1 deg. F. will increase fuel consumption by about 5 per cent. In some cases the conditions to be maintained are prescribed. Thus the heating and ventilation of most industrial premises must be in accordance with the provisions of the Factories Act, which provides, *inter alia*, that in workrooms in which a substantial portion of the work is done sitting and does not involve serious physical effort a temperature of at least 60° F. is required after the first hour. Also, in many towns, the heating and ventilation of cinemas and similar places of public assembly are subject to the regulations of the Local Authority.

Many different methods are employed for heating buildings, but they can be broadly classified as *local heating* and *central heating*. With local heating, fuel is burned in grates or stoves, or electricity or gas consumed, within the space to be warmed. The comfort effect of such heaters depends largely upon the radiation from flames or other sources at high temperatures. Radiation passes through the air almost unabsorbed, but when it impinges upon solid surfaces these become warmed and heat the air by convection. When there is a considerable amount of radiation, comfort can be obtained with somewhat lower air temperatures than are necessary with comparatively low temperature sources of heat, such as hot water or steam radiators, which, despite their name, give off most of their heat by convection, and warm the air directly. In such cases, comfort depends mainly upon air temperature, and this method of heating is therefore known as space heating. Space heating is usually provided by some form of central heating, in which heat is generated at a central point, and transmitted through pipes or conduits to the points where it is required.

In this chapter, various forms of central heating are considered. The special problems of *district heating*, in which a number of buildings are served from a central boiler house, are not dealt with, but many aspects of space heating are common to both central and district heating systems.

SPACE HEATING

The problems of space heating are closely related to the laws of heat transmission discussed in Chapter 9. When the temperature inside a building is higher than the temperature outside, heat flows from the inside to the outside.

The heat flowing from a building is termed the *heat loss*, and the heat loss occurs in several ways. To maintain the internal temperature, heat must be supplied to the building at the same rate at which heat flows from it. It follows that if the heat loss is small, the amount of heat required to maintain the internal temperature is also small; the heat loss is therefore of special importance in considering the amount of fuel required for space heating.

An important example of heat loss is that in the air that must be provided for ventilation in all occupied buildings, and that finally escapes to the atmo-

sphere outside, carrying with it the heat that has been used to warm it. The amount of air provided for ventilation purposes is expressed as *air change*. The rate of air change should therefore be limited to the minimum necessary, depending on the size of the room, the number of persons in it, and the type of work performed. If the air change is excessive it will cause a serious waste of fuel, and every precaution should be taken to avoid a greater air change than is necessary for health reasons.

Heat is also lost from a building by conduction through the structure. When the temperature inside is higher than the temperature outside, heat is transmitted through the walls, roof, floor, windows, and other parts of the fabric of the building. Some building materials and constructions have a lower heat transmittance or U-value* than others, and hence a greater insulating value. Constructions that have high insulating values are, by definition, more resistant to the escape of heat than those with lower values, and the heat loss can be reduced either by methods of construction providing a barrier to the conduction of heat, or by the incorporating, in the building structure, materials that are resistant to the conduction of heat. Structural insulation substantially reduces the total heat loss from a building.

In particular, insulation of the roofs of single-storey buildings not only reduces the heat loss in winter, but can also keep the building cooler in summer. The Building Research Station manual, "The Thermal Insulation of Buildings"¹ provides a convenient guide to the use of heat-insulating materials, their performance and their cost.

In designing a space heating installation, the total heat loss is calculated as the amount of heat required to maintain the required internal temperature when the temperature outside is taken as being at an assumed minimum value, usually, in calculations for heating systems in Britain, 30° F. The total heat loss calculations will make allowance for the air change, and for the conduction losses through the structure, and should also allow for the degree of exposure of the building, the height of the heated spaces, and the intermittency of the heating requirements. Recommendations as to procedure in design are contained in the guide issued by the Institution of Heating and Ventilating Engineers on this subject.² The design of the heating installation should also take into account the thermal time lag of the building, or the time required for response of the building temperature to changes in external conditions and to changes in the output of the heating apparatus. The matter is discussed in some detail³ in the publication "Post-War Building Studies," No. 33.

TYPES OF CENTRAL HEATING SYSTEMS

A. LOW PRESSURE HOT WATER HEATING WITH RADIATORS AND PIPES

The most widely used method of central heating in this country is by means of low pressure hot water with a cast iron sectional boiler and cast iron radiators. Water is heated in the boiler to a temperature depending upon the external conditions but not exceeding 180° F. in cold weather. The water from the boiler circulates through a system of pipes to the various radiators, and returns from the radiators through the return pipes to the boiler, the temperature of the water returning to the boiler being lower than the temperature of that leaving the boiler. This water again passes through the boiler and is heated

*The U-value is the overall thermal transmittance in B.t.u. per sq. ft. per hour per deg. F. difference between indoor and outdoor air temperatures. It is a figure calculated for each individual construction of wall, floor, roof, etc., the value in each case depending upon various factors—materials of construction, thickness, degree of exposure to wind, dimensions of air space, etc. Tables of U-values are published in text books on heating.

to the flow temperature, and the circulation continues in this manner. The same water is circulated continually and after the initial filling of the apparatus only a very little make-up water is occasionally required.

In small installations, where the layout is favourable, the system may be designed for a natural gravity circulation, utilizing the difference in weight between the hot flow water and the cooler return water to promote circulation round the system. This is possible only where these circuits are not very long and the heating surface is at a reasonable height above the boiler.

In larger installations or where the layout does not allow circulation by gravity, the water is circulated mechanically by an electrically driven centrifugal pump (or by a turbine driven pump if steam is available) as in Fig. 1. It is usual to install two pumps, one acting as a standby in case of breakdown.

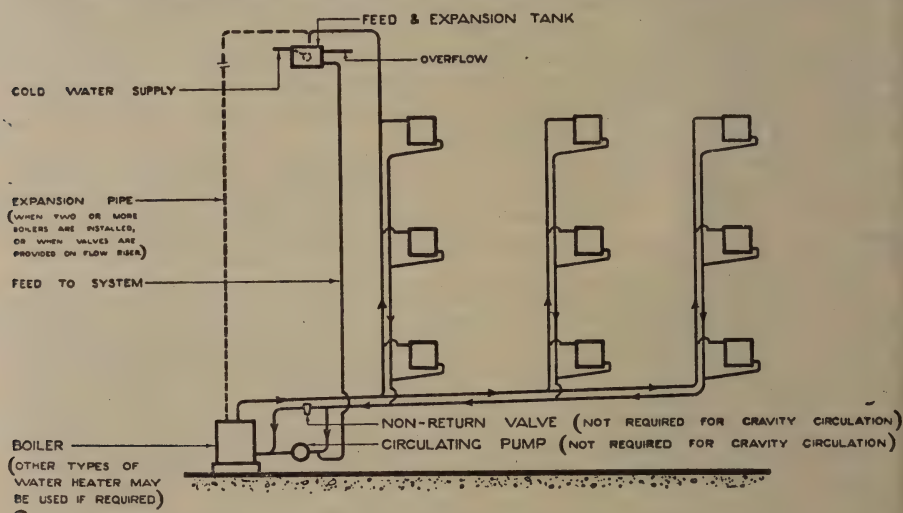


FIG. 1. Low pressure hot water heating with radiators and pipes.

The pumps are fitted on a by-pass and provided with isolating valves; a non-return valve is fitted in the main pipe between the suction and delivery connections to the pumps. The pumps are usually on the return main, delivering into the boiler. While the pump is running the non-return valve is held in the closed position by the pressure differential created by the pump, but if the pump should stop the valve opens and a gravity circulation will continue in so far as the design of the system makes this possible. This arrangement guards against the possibility of a complete stoppage of circulation in the event of pump failure with consequent overheating and possible damage to boilers.

The size of the pumps installed varies according to the size and layout of the system and they may work against heads varying between 3 and 25 feet. The various pipe circuits are arranged and the sizes calculated so that the total resistance set up by the flow of water round each complete circuit is approximately the same. This will be the head against which the pump will operate and care must be taken to select a pump working at high efficiency under the particular conditions.

The quantity of water circulated by the pump is constant, and variations in heat requirements in the building are met by varying the temperature at which the water leaves the boilers between a maximum of about 180° F. in coldest weather down to about 105° F. in mild weather.

Under certain conditions corrosion troubles arising from condensation

from flue gases have been known to occur when heating boilers are operated at low temperatures. This has been overcome in some cases by installing a cross-connecting pipe between the flow and return mains with a mixing valve, set to maintain the temperature of the return water entering the boiler above pre-determined figure.

Low pressure hot water heating systems are open to the atmosphere, so the pressure on the boiler depends upon the static head of water in the system. A feed and expansion tank is installed above the highest point in the circulation and connected to a point near the boiler by means of a feed pipe. The water level in this tank is maintained by means of a ball valve. All pipes are arranged with a slight slope so that any air in the system will collect at definite high points. At these points open air pipes are provided, these being carried to a height well above the water level in the tank or if this cannot conveniently be done automatic air release valves are used instead, but the former course is preferable.

In most installations radiators are of the cast iron sectional type. The heat from the water in the radiators is conducted through the metal and raises the temperature of the air in immediate contact with the surface. This warmed air rises, cooler surrounding air takes its place and a continuous circulation of air is thus induced over the radiator. The hot surface of the radiator also emits about 15 per cent. of its heat output directly by radiation.

As heat is lost from the rooms mainly through the external walls, radiators are placed against these as far as possible. Windows cause down-draughts of cold air, and it is usual to place radiators beneath them to counteract this effect. In a similar way down-draughts from skylights or windows at high level may be guarded against by running pipes beneath them. As there is a slight temperature gradient between floor and ceiling in a room heated in this manner, where the height exceeds about 12 feet extra heating surface is installed to ensure that the required temperature is obtained in the occupied stratum.

The amount of heating surface in the different rooms of a building must be carefully proportioned according to the size of rooms and the area of walls, windows and other surfaces exposed to the outside air. Different temperatures may also be required in different rooms. The rate of ventilation must also be taken into account and allowance made for warming all incoming air to the temperature of the room. In offices and similar rooms the number of air changes allowed is one-and-a-half or two per hour, but in buildings such as schools or hospitals higher rates of air-change are necessary. In industrial buildings the rate of ventilation will depend upon the number of occupants and the nature of the processes.

Boilers, pipes and any other surfaces which are not used for direct heating purposes should be insulated with non-conductive material to prevent waste of heat.

B. LOW PRESSURE HOT WATER HEATING WITH PANELS

Heating by means of radiant panels is often adopted in certain types of buildings such as offices, schools, hospitals and public buildings. The heat is imparted to the rooms by large plane surfaces warmed to a temperature above that of the air in the room. These panels may be in the ceiling, walls or floor, but ceiling panels are generally used. (Fig. 2.)

One type of panel consists of a flat steel or cast iron plate backed with small waterways in the form of ribs through which the hot water circulates in exactly the same way as for an ordinary radiator. These panels are superimposed upon or recessed into the structure of the building and the backs are insulated with non-conducting material. The pipes connecting to them are

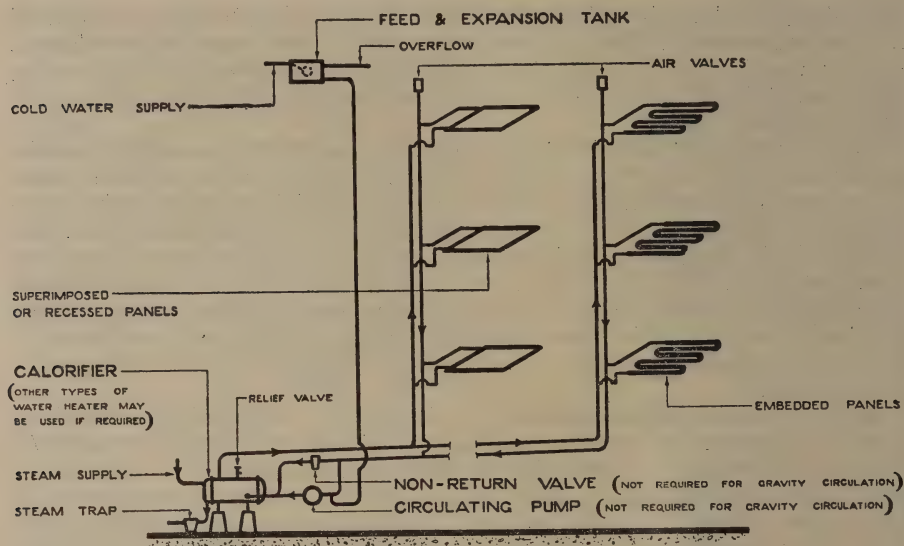


FIG. 2. Low pressure hot water heating with panels.

usually concealed so that the heating device is hardly perceptible. In this type the water may be circulated at the same temperature as it would be in an ordinary radiator heating system.

Another method is to embed small pipes, of $\frac{1}{2}$ – $\frac{3}{4}$ inch bore, in the structure itself. Pipes made up into grids or coils are embedded as panels in the concrete floor or ceiling and the warmed area of the floor or ceiling radiates heat to the room. The flow and return connections to the panel coils are also embedded in the structure so that the heating panel is not visible. Pipes solidly embedded in concrete in this way are heated only to a moderate temperature. The temperature of the circulating water usually does not exceed 120°F. , and may be varied as follows:

Outside shade temperature: $^{\circ}\text{F.}$	55	50	45	40	35	30
Flow temperature: $^{\circ}\text{F.}$	85	90	97	105	112	120

A suitable method of plastering is adopted to guard against the plaster cracking.

There are several methods of floor heating by which the pipes are laid in a hollow space beneath the normal floor finish so that the whole or part of the area of the floor is warmed, but an uncomfortably high floor temperature must obviously be avoided.

As heating by panels, particularly ceiling panels, depends upon radiation rather than convection, that is to say it heats the objects in a room directly without necessarily also warming the air, the rate of ventilation does not have such an effect on comfortable conditions in the room as it would have with ordinary convection heating.

It is not possible to generalize about the respective fuel consumptions of panel heating and convection heating systems, since much depends on the method of control and in particular on the intermittency or otherwise of the space heating requirements. Where the conditions require continuous heating they will tend to favour panel heating, but where intermittent heating only is required, conditions will tend to favour intermittently operated convection systems.

C. LOW PRESSURE STEAM HEATING

Steam at low pressure is often used for heating, particularly in industrial premises where a plentiful supply of steam is available (Fig. 3). Exhaust

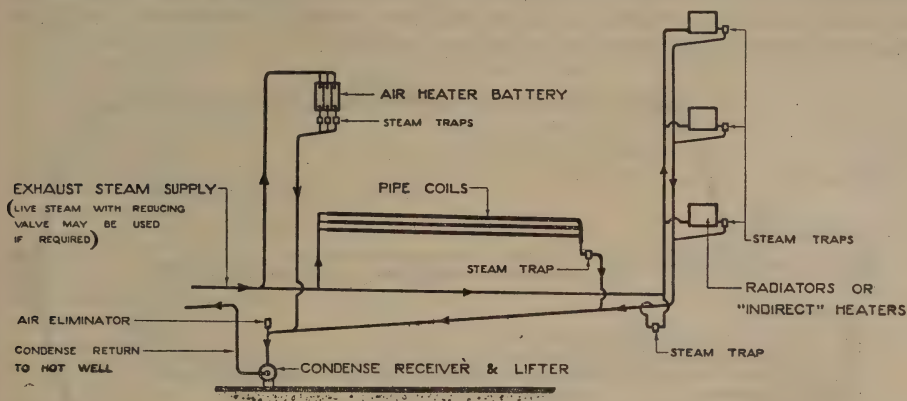


FIG. 3. Low pressure steam heating.

steam from turbines or engines may be utilized where circumstances permit. Where sufficient steam is available from sources of this nature it provides an economical method of heating. The back pressure on the engine must, of course, be given consideration.

Steam for heating at low pressures is also produced in various types of boilers designed specially for this purpose. The boiler pressure used is generally between 3 and 10 lb. per square inch, and cast iron radiators of the type used for hot water heating may be used with steam at this pressure. The steam is conveyed to the radiators by one pipe, and is condensed in the radiators. It is then discharged by a steam trap into a condensate pipe through which it returns to the boiler.

Steam traps are fitted to the steam main at intervals to drain away any condensate which may collect, thus keeping the steam as dry as possible. The return lines are arranged to fall back to the boiler house so that the condensate will return by gravity flow. If exhaust steam is being used the condensate will be returned to the hot-well (providing it is in a suitable condition for re-use).

When steam is generated in low pressure boilers specially designed for heating, the condensate is very often returned to the boilers by gravity without the use of a feed pump. The same water is repeatedly evaporated and condensed so that there is very little make-up required. (In this connection see also "Automatic Boiler Feeder", page 651.)

The system is often used in workshops, etc., for heating by means of pipe coils. The output from radiators, etc., will, of course, depend upon the surface temperature which, in turn, will depend upon the steam pressures. Radiators and pipes using low pressure steam have surface temperatures in the region of 230° F. A disadvantage of ordinary steam heating is that the temperatures cannot be varied to suit external conditions; the system maintains a constant heat output.

The pressure in the radiator will be equal to the boiler pressure *minus* the drop in pressure in the piping. Consequently pipe sizes are proportioned to provide a pre-determined pressure at each radiator or other heating device.

Where steam is available for heating and it is desired to heat by low pressure hot water, this is done by means of calorifiers which consist of a steel cylinder containing a battery of steam pipes for heating the water which is

then circulated through a heating system in the usual way. Calorifiers are also used for supplying hot tap water, and since for this purpose the water in the casing of the calorifier is subject to constant change as hot water is drawn off and replaced by make-up water, the materials from which the calorifier is constructed must be suitable for use with the particular water supply. Fig. 4 shows a storage type of hot water supply calorifier.

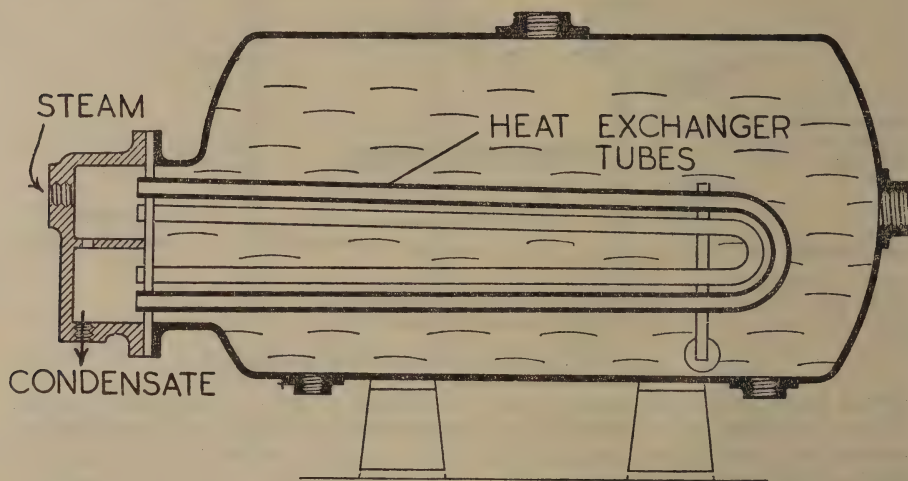


FIG. 4. Hot water supply storage calorifier.

D. VACUUM STEAM AND VAPOUR HEATING SYSTEMS

The vacuum system consists in essence of a boiler, pipework and radiators arranged in a similar manner to an ordinary low pressure steam system, the main difference being the addition of a vacuum pump and receiver on the main return line close to the boilers.

The duty of the pump is to maintain a partial vacuum in the return line and deliver the condensate back to the boiler. This assists in preventing air from accumulating in the radiators and ensures more uniform heating. The rate of flow of steam through the radiators may also be varied by changing the amount of vacuum. The return of condensate from radiators is more positive and under control, and if necessary condensate may be lifted so that difficulties due to unfavourable levels may be overcome.

The vacuum system of steam heating may also be employed where exhaust steam from turbines or engines is available for heating purposes, and in such cases the system is advantageous in that the low pressures at which the steam may be circulated reduce the back pressure on the engine or turbine.

A further modification is the "sub-atmospheric" system in which the boiler pressure is allowed to vary from a few pounds per square inch above atmosphere down to a vacuum of about 25 inches of mercury, so that steam is generated at temperatures varying from about 220° F. down to about 130° F. A vacuum pump is provided to deal with the condensate. The steam pressure at radiator inlet and vacuum at outlet, produce a differential pressure causing the steam to flow through the radiator. The rate of flow may be controlled by varying the differential pressure according to weather conditions. Air is eliminated from the system by the vacuum pump and a positive return of the condensate is provided. It is also possible to control individual radiators by means of regulating valves.

E. HIGH PRESSURE HOT WATER HEATING

The temperature at which water boils is governed by the pressure to which it is subjected; the higher the pressure the higher is the boiling point. Advantage has been taken of this fact in a development in hot water heating, chiefly for industrial applications but also used in other buildings, by the use of a completely closed system of pipework connected to a steam boiler, but terminating below the water line, so that the water in the boiler may be circulated through the pipe system (Fig. 5). Steam is raised in the usual way, the water line being maintained at a rather higher level than normally. The steam in the steam space acts as a cushion to take up the expansion of the water in

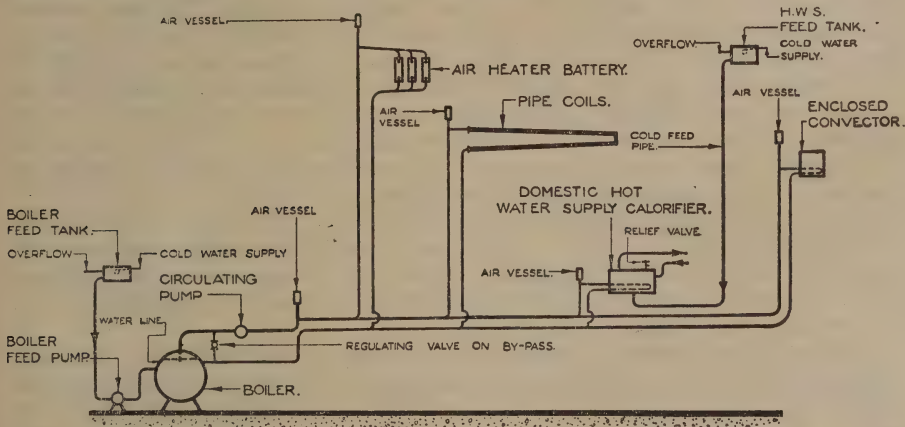


FIG. 5. High pressure hot water heating.

the system as its temperature rises, and the boiler pressure is imposed upon the whole of the system. Where more than one boiler is installed these are connected together above and below the water line by means of balance pipes to ensure a common pressure and water level in all boilers. Working pressures up to 250 lb. per square inch are used, but a common figure is 150 lb. per square inch.

The water from the boilers is circulated through the pipe system by means of centrifugal pumps. The flow temperature of the water leaving the boilers will be that corresponding to the steam pressure in the boilers; i.e. if the boiler gauge pressure is 150 lb. per square inch the water temperature will be 366° F. Any reduction in pressure will therefore cause some of the water to flash into steam; to guard against this a by-pass is installed between the return main and the flow main.

The pumps are placed on the flow main immediately after the by-pass connection so that cooler return water can be mixed with the boiler water when passing through the pump. The temperature of the water flowing to the system may therefore be varied by controlling the proportions of water at the two different temperatures.

Circulating pumps are installed on the flow so that the additional pressure imposed on the system helps to lessen the possibility of flashing. The connection between boilers and pumps must be as short as possible.

An installation of this type can provide heat for process work also. Whilst the temperature required for this purpose will be constant throughout the year, that required for heating will depend upon the outside weather conditions, and will not be required at all during the summer months. Separate heating and process mains are therefore often installed.

The boilers are usually worked at full pressure at all times, so as to maintain a constant pressure on the system; variations in temperature requirements are met by the above mixing arrangements and variations in load by varying the output of the boiler or boilers in operation.

For collecting the air in the system air vessels are provided at suitable points, from which it is released by means of air pipes and valves. It is most important that all air be excluded from the system before it is put into operation, otherwise serious waterhammer may be produced.

The pipe sizes are calculated in a similar manner to those for low pressure hot water heating, allowance being made for the effect of temperature and pressure on the viscosity of the water which affects the resistance to flow and consequently the size and power of the circulating pumps. The temperature drop round the system varies according to the initial pressure, but temperature drops of the order of 50–100° F. are common, an average being about 70° F.

The necessity to provide adequate insulation of boilers and heating systems has already been referred to. The importance of insulation in contributing to efficient operation can hardly be over-emphasised.

Ordinary cast-iron radiators cannot be used for high pressure hot water heating as they cannot withstand the pressures involved.

Heat is imparted to the building by means of unit heaters, pipe coils and, in small spaces such as offices, by enclosed convectors containing pipe coils capable of withstanding the pressure. Valves and fittings are of special types.

Hot water for domestic purposes is heated by means of calorifiers served by the high pressure hot water mains.

If steam is required for process work at high pressures it may be taken direct from the boilers, but low pressure steam may be generated where required by means of a steam raiser connected to the high pressure hot water mains. The steam raiser comprises a mild steel cylinder fitted with the usual boiler mountings and provided with a small electrically driven centrifugal pump for feeding purposes. This is generally controlled by a float-operated switch to maintain a constant water level. The high pressure water is circulated through a pipe coil immersed in the water, causing evaporation and the production of steam. The circulating water should be controlled by a valve operated by a pressure switch attached to the steam space of the cylinder so that constant steam pressure is maintained. The pressure that can be raised depends upon the temperature of the high pressure water; with water at 350° F. it is possible to generate steam up to pressures of about 30 lb. per square inch.

F. MEDIUM PRESSURE HOT WATER HEATING

It is sometimes advantageous to have the circulating water temperature in a hot water heating system somewhat higher than that obtainable with a low pressure system but without unduly increasing the cost of boilers, pipes, fittings, etc. In these circumstances a medium pressure hot water system may be employed. The system in this arrangement is somewhat similar to the low pressure hot water system, but is entirely closed, i.e. it has no open vents to atmosphere, and it has a working pressure not exceeding about 50 lb./sq. in. It is possible to operate this system with a flow temperature of up to 230° F. The correct pressure is obtained by installing a cylinder containing air and water, the air acting as a cushion and the water being added to or bled from the cylinder to maintain the required pressure.

G. COMBINED HEATING AND VENTILATING SYSTEMS

Heating by any of the methods described may be combined with ventilation. Two main types of such systems are described below.

For theatres and similar places where a large number of people are assembled a positive method of ventilation is necessary to ensure an adequate quantity of fresh air, and a combined system of heating and ventilation is installed (Group A). Air from the outside is drawn over a heater by means of a fan which discharges the warmed air into a duct system connecting to grilles of suitable size and location in the various spaces to be dealt with. (Fig. 6.)

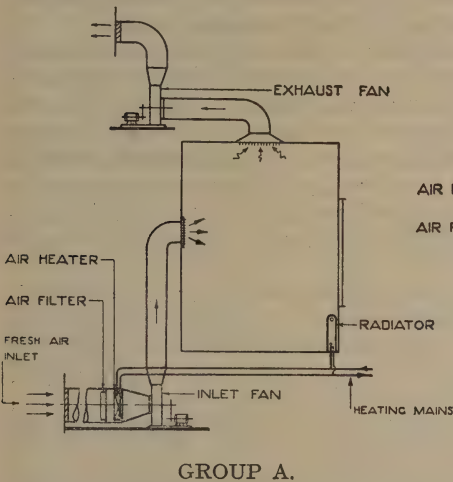


FIG. 6. Combined heating and ventilating plants

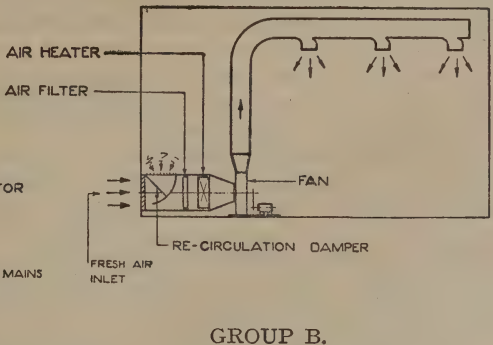


FIG. 7. Combined heating and ventilating plants

The air is heated so that it enters the rooms at approximately the same temperature as the air in the rooms. Direct hot water or steam heating surface is also installed to make good the heat loss through walls, windows, etc.

An extraction fan connected to a separate duct system exhausts the air from the rooms through grilles so placed in relation to the fresh air grilles that an equable distribution of the air is obtained throughout the space concerned.

Arrangements may be made for part of this extracted air to be re-circulated through the fresh air ducts where it is mixed with a proportion of fresh air and returned to the rooms. This arrangement economises in fuel consumption, but depends upon the condition of the exhausted air and to some extent upon whether the air is passed over air filters or washers before being re-delivered into the rooms.

The air heaters may be served by hot water or steam produced in heating boilers of the usual type, and the boilers may also serve for direct heating by radiators or other means.

Alternatively, air may be delivered into the rooms at a higher temperature, so that after giving up heat to the cooler room surfaces its final temperature is equal to the room temperature required (Fig. 7). This method, Group B, is largely used in workshops and factories.

In industrial buildings heated by unit heaters fresh air may be necessary to replace large quantities of air exhausted by dust-collecting plant, fume exhausting systems, etc. This is usually accomplished by arranging the unit heaters to draw air from outside the building through metal ducts, re-circulating dampers being provided on these ducts so that all or part of the air passing through the heater may be taken from the building when additional fresh air is not required.

H. HEATING BY ELECTRICITY

When electricity is applied to the heating of large buildings it is usually by the thermal storage system. The electricity supply is used during off-peak periods for warming up water in large storage cylinders which are very efficiently insulated to reduce heat loss, the heat stored in the water being sufficient to supply all heating requirements during the period when current is switched off. This water is circulated by a pump through an ordinary hot water heating system, the storage cylinders merely replacing the more usual boilers.

The temperatures to which the water may be warmed will govern the amount of useful heat that can be stored in each cubic foot of water, and the maximum temperature depends upon the static head on the storage cylinders, i.e. the higher the building being heated, the greater the amount of heat storage possible in a given volume. The maximum storage temperature at the end of the off-peak period should be about 20° F. below the boiling-point of water at the static head concerned. This temperature will usually be above the boiling-point of water at normal atmospheric pressure and much too high for circulation round the heating system.

The water in the heating system is therefore circulated by means of centrifugal pumps and high temperature storage water is added to the circulating water through a thermostatically controlled mixing valve in such quantities as are required to maintain the necessary temperature of the circulating water. This temperature will vary according to the outside weather conditions, etc., and will also depend upon the type of system, e.g. it will be lower for an embedded panel system than for a radiator system.

During the daytime there will be a gradual fall in the temperature of the storage water and by the time the current is again switched on the storage temperature may have fallen very nearly to the flow temperature to the heating system.

The water may be heated by electrical immersion heaters in the cylinders, or more frequently by an electrode water heater which consists of a mild steel shell containing water in which are immersed three electrodes connected to the three phases of the supply. A small quantity of a suitable chemical is added to the water to increase its conductivity to the necessary value. The current then passes through the water between the electrodes, so heating it. The shell of the heater is connected to the neutral of the supply and is earthed. (It should be noted that a supply must not be earthed in this way without the permission of the electricity authorities who must, in any case, be consulted before any installation is made.) The electrode heater is usually connected to the storage cylinders by means of flow and return pipes and the water is circulated between them by "primary" circulating pumps.

A recent development of the electric thermal storage method of heating is electrical floor warming, in which electric heating cables are installed in concrete floors. Small metal ducts are embedded in the concrete floor, and the electric heating cables are later drawn into the ducts or they can be directly embedded in the floor in which case the ducts are unnecessary. When installed in this way, the use of electricity can be confined to the off-peak periods; this generally permits the use of an advantageous 'off-peak tariff. During these periods the concrete floor is heated to the required amount, which can be controlled by a thermostat, and the heat then stored in the floor is sufficient to maintain the required degree of comfort through the period when the electrical supply is cut off by the time switch. The floor is warmed to a maximum surface temperature of around 70° F., and it is claimed that most types of floor finishes and coverings can be used. Buildings warmed in this way may also have supplementary electrically heated wall panels.

As in the case of the embedded hot water panel system described in B above, the economy of this method of heating compared with other methods will depend on the effectiveness of the control arrangements, and (as in B) on whether the space heating requirements are continuous or intermittent.

Another arrangement of off-peak electric thermal storage heating uses storage heaters which consist of refractory concrete blocks or similar material through which electrical heating elements are threaded, the whole being enclosed in an insulated sheet steel casing. They are made in several sizes and loadings. Electricity is used during the off-peak periods and warms the mass of concrete material to provide a surface temperature of between about 160° F. to 220° F., and the room is warmed by slow cooling of the heaters during periods when electricity is not being consumed. This type of electric thermal storage heating is stated to be suitable for premises such as shops, offices and workrooms.

HEAT PUMPS

During recent years attention has been given in an increasing degree to the possibility of carrying out space heating by means of the "heat pump" because it offers the attraction of reducing the fuel consumption to very low level, giving in favourable circumstances an apparent efficiency of fuel utilization of over 100 per cent.

Many different systems for heat pumps have been suggested and tried as ways of applying the principle of the heat pump; all are essentially the same from a strictly thermodynamic viewpoint, differing only in the way in which the theoretical possibilities are put into practice. The most popular and probably most useful system corresponds to the vapour compression type of refrigerator, as shown diagrammatically in Fig. 8.

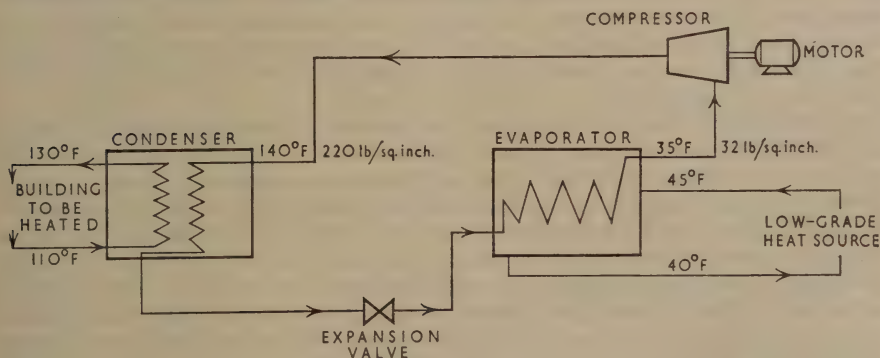


FIG. 8. Diagram illustrating principle of the Heat Pump.

A suitable liquid known as the refrigerant* is contained in an "evaporator" where it is allowed to boil at low pressure, taking in heat from the surroundings at a comparatively low temperature to supply the latent heat of vaporization of the liquid. The vapour at low temperature and pressure is then compressed through a mechanical compressor to a pressure high enough to force condensation to take place at a temperature useful for space heating. This condensation takes place in a vessel, known as a condenser, where the latent heat of condensation is taken away by water flowing through tubes, the

*Ammonia, carbon dioxide, sulphur dioxide, methyl chloride, are all possible refrigerants. The range of chemicals known as *freons* have proved to be specially useful because of their non-toxic and non-explosive characteristics. These are mainly fluorine (and other halogen) derivatives of hydrocarbons, especially 'Freon 12', dichlorodifluoromethane.

water being thus heated to a useful temperature. The condensed liquid is passed through a suitable throttle back to the evaporator where the process is repeated. It will be seen that heat is extracted from comparatively low temperature surroundings in the evaporator; this is the essential operation when the process is used for refrigerating purposes, whereas the rejection of heat in the condenser is the basis of its use as a heat pump.

It can be seen that the amount of heat usefully rejected in the condenser must be equal to the sum of the heat absorbed in the evaporator and the heat equivalent of the work of compression. The heat input is of course the motive energy to drive the compressor and it follows that the heat output from the condenser is substantially above the heat equivalent of this energy. This ratio of heat output to energy supplied is known variously as *coefficient of performance* (C.O.P.); *reciprocal thermal efficiency* (R.T.E.), or *performance energy ratio* (P.E.R.). In typical cases it lies between 2 and 4. For a floor-heating system recently (1955) installed, the C.O.P. value was 3.4.

The ratio of useful heat obtained to energy input rises proportionately as the difference in temperature between the cold side and the hot side of the plant is reduced. In practice this means that heat pumps become more effective the lower the temperature at which heat is required for use. Heat pumps would thus be more efficient with panel heating than in a radiator system.

The low temperature side of the plant must be continually supplied with heat to avoid complete freezing up. Probably the most useful source is water from a river, lake, or canal, etc. Satisfactory results have been achieved with air as the low temperature source but this naturally leads to bulky evaporators to provide the necessary surface area and in some atmospheric conditions gives rise to frosting trouble, the avoidance of which complicates the circuit. Furthermore, air is at its lowest temperature when heat is needed. Another, apparently less satisfactory, heat source is the ground, from which heat has been extracted by laying down, several feet underground, pipes through which the cold refrigerant is passed. This pipe system then takes the place of the more normal evaporator.

The heat input to the system has been described above as the motive energy for driving the compressor. It is important to note that the fuel required to provide this motive power (e.g. coal at the power station; oil in an oil engine; or gas in a gas engine) has a total thermal value very much more than the heat equivalent of the output of the electric motor or the engine so that an overall thermal balance (heat produced vs. fuel consumed) is not so attractive as might appear at first sight. In suitable cases this has led to the expedient of collecting the exhaust heat from a prime mover and adding it to the heat produced by the heat pump, so that good use is made of all the thermal energy in the original fuel. In this way it is possible to get a thermal efficiency of the order of 150 per cent. of the heat content of the raw fuel.

In assessing the potential value of a heat pump for a particular set of circumstances, attention must of course be given not only to the potential fuel saving but also to the capital expenditure and the maintenance costs. A heat pump will undoubtedly be more expensive than a boiler for the same output, since it contains moving parts; it will probably need more maintenance and have a shorter life. A heat pump also requires a rather more expensive fuel, e.g. electricity or oil or gas, than a solid-fuel-fired boiler, so that the increased output is not always reflected in a financial saving.

The economics of fuel costs favour the heat pump when account is taken of the labour costs of handling solid fuel.

Considerations such as these lead to the following conditions which especially favour a heat pump as a means of space heating:

1. The desire to avoid solid fuel, including the desire to minimise labour charges.
2. A high load factor on the heating plant (to pay off capital charges quickly).
3. The possibility of using the heat at comparatively low temperatures.
4. An immediately available and reliable source of low grade heat, such as warm effluent from an industrial process.
5. Possibility of using the system for supplying heat in the winter and for cooling in the summer, or supplying heat to one establishment and for cooling another neighbouring establishment. A good example would be an ice rink next door to or near a dance hall.

It should also be remembered that since a heat pump is in fact a refrigerator, cold storage can be provided from the same plant with negligible additional capital costs. This can be an overriding advantage in some circumstances and has already been exploited in the domestic field to the extent of the development of a heat pump based essentially on the normal domestic refrigerator, the arrangement being that refrigeration is provided in a larder while the same apparatus keeps a constant supply of hot water available for domestic purposes.

AIR CONDITIONING

When it is required, for amenity or for process purposes, to maintain both the temperature and humidity of the air at constant levels, irrespective of outside conditions, full air conditioning must be employed. This involves refrigeration, at least over a great part of the heating season, and is comparatively expensive. Briefly, the temperature of the incoming air must be reduced to the dew-point of the final condition required. This is effected by passing the air through a chamber in which it is intimately mixed with a fine spray of water, chilled by refrigeration, the temperature being adjusted so that the air leaves the chamber saturated at the dew point. Any excess moisture removed from the air is carried off in the spray, which is continually recirculated over the evaporator coils of the refrigeration plant. The air leaving the spray chamber passes through a coil of pipes, heated by hot water, where its temperature is raised to the desired level and the air enters the conditioned space with the required temperature and relative humidity.

The temperature of the spray and of the heater are automatically controlled, preferably by elements situated in the conditioned space, and wherever possible, arrangements are made for recirculating a large proportion of the conditioned air after it has passed through the space. The balance of fresh air is admitted from outside to join the recirculated air before entering the spray chamber.

If a full air conditioning plant has to be designed, consideration should be given to the possibility of using the condenser as the heating coil. Usually the condenser is air- or water-cooled outside the building, but this involves great waste of heat. Using the condenser as the heater constitutes a heat pump, with considerable savings in both capital and operating costs. An obvious precaution is that the condenser coils within the heater casing must be entirely jointless, in order to eliminate the slightest risk of the refrigerant finding its way by leakage into the air stream. (See also Chapter 25.)

TYPES OF BOILERS

The most popular type of boiler for low pressure hot water heating and low pressure steam heating is the sectional boiler (Fig. 9). This is usually of cast iron, although mild steel boilers of this type are sometimes used.

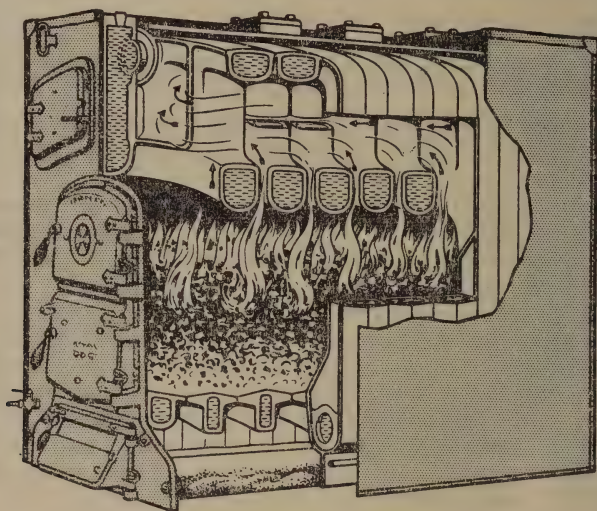


FIG. 9. Cast iron sectional hot water boiler.

CAST IRON SECTIONAL BOILERS

The sectional cast iron boiler is inexpensive, independent of brick settings, and easy to install. Being in comparatively small sections, it is easy to transport, and to fit into places having very limited access. A damaged section may be replaced without having to renew the whole boiler. The boiler is built up of sections held together by bolts, the waterways being connected by nipples. In some types the sections are mounted on a separate base, in others the sections are designed to stand direct on the floor.

If an installation is increased in size the extra load may be carried by adding more sections to the boiler, up to its maximum limit in length. The permissible length depends upon the method of firing adopted, being greater for mechanical firing than for hand firing. When fired by hand, smokeless low volatile fuels are used.

For hot water heating, the flow water leaves the top of the boiler, and the cooler return water enters at low level. Return connections at both sides are preferable to ensure good circulation of the water within the boiler. For this reason, also, it is preferable that flow and return connections be made at opposite ends of the boiler.

Many of these boilers have ordinary grille firebars which may tend to become distorted and burn away in time and require periodical replacement. Some are provided with waterway firebars which form part of the sections. These have two advantages; the temperature of the firebars is kept low so that they cannot burn out, and the disposition of water-cooled firebars increases the overall efficiency of the boiler.

The front section of the boiler is usually provided with three central doors; the lowest is the ashpit door, the next the clinker door for cleaning out the fire, and the top one is the fuel door through which fuel is added to the fire. There are also two or more doors to give access to the boiler flues for cleaning purposes.

This type of boiler is suitable for low pressure hot water heating systems with static pressures up to 100 feet. For low pressure steam heating the maximum permissible working pressure is 15 lb. per square inch.

When used for low pressure steam heating, steam drums may be mounted

above the boiler. The boiler is then completely filled with water and the working water line maintained at about the centre line of the drum, instead of a few inches above the crown of the furnace. Water and steam gauges are mounted on the drum. The steam supply is taken from the top of the drum. Make-up water and condensate are returned to the boiler in various ways, according to the type of system.

These boilers are generally designed so that the gases of combustion leave the firebox at the back, then pass forward through flues to the front, returning to the back and passing out through a smoke nozzle at the back. The heating surface exposed directly to radiation from the fire is known as primary heating surface, and that in the flues, secondary heating surface. For efficient working, the chimney should be of the correct size and provided with access for cleaning.

The draught is controlled by dampers which are normally manually operated although thermostatically controlled dampers can be provided. The ashpit damper forms part of the ash door and controls the passage of air through the grate. A secondary air damper is provided in the firing door, usually arranged so that air passing through it is preheated by some simple device before entering the combustion chamber. The flue damper is usually of the butterfly type fitted in the smoke nozzle at the back of boiler and operated by a rod extended to the front.

MILD STEEL SECTIONAL BOILERS

Sectional boilers, similar in design to the cast iron types, are also made of mild steel plates welded together. They are more expensive than cast iron boilers, but have certain advantages. They can withstand somewhat higher pressures and may be installed for hot water heating in taller buildings, or may be used for steam heating at pressures up to 25 lb. per square inch. As mild steel is less brittle than cast iron, it is less liable to accidental damage. The sections of steel boilers are not connected by nipples, but usually by external flow and return headers separately connected to each section.

GRAVITY FEED BOILERS

A variation of the foregoing types is the cast iron or mild steel gravity feed boiler (Fig. 10). This type is constructed on a similar principle to the ordinary sectional patterns, except that, incorporated above the grate, there is a fuel bunker or hopper so arranged that as the fuel on the grate is burned, fresh fuel falls on to the grate to take its place. The grate is often sloping, the fuel being fed on to the higher end, gradually moving down to the lower end so that by the time the lowest point is reached it is completely burned, the ashes falling through the grate bars into the ashpit below. The aperture through which the fuel falls on to the grate is adjustable so that the thickness of the fire may be controlled according to requirements. The rate of combustion is under control, either by the use of thermostatically operated dampers or a thermostatically controlled forced draught fan delivering air into the furnace for combustion.

Anthracite or coke may be used, a fairly small size being required for most types. The storage capacity of the fuel hoppers may be up to twenty-four hours' supply, and if the main fuel bunkers are above the boilers so that they may be refilled by means of simple chutes, handling of the fuel is practically eliminated. With automatic draught control, boilers of this type may therefore be left for fairly long periods without attention, apart from occasional clinking and removal of ash. Air-tight lids are provided to the hoppers to prevent the possibility of the fire creeping back from the grate into the hopper. It is essential that the seatings have proper attention so that the lids may be closed tightly.

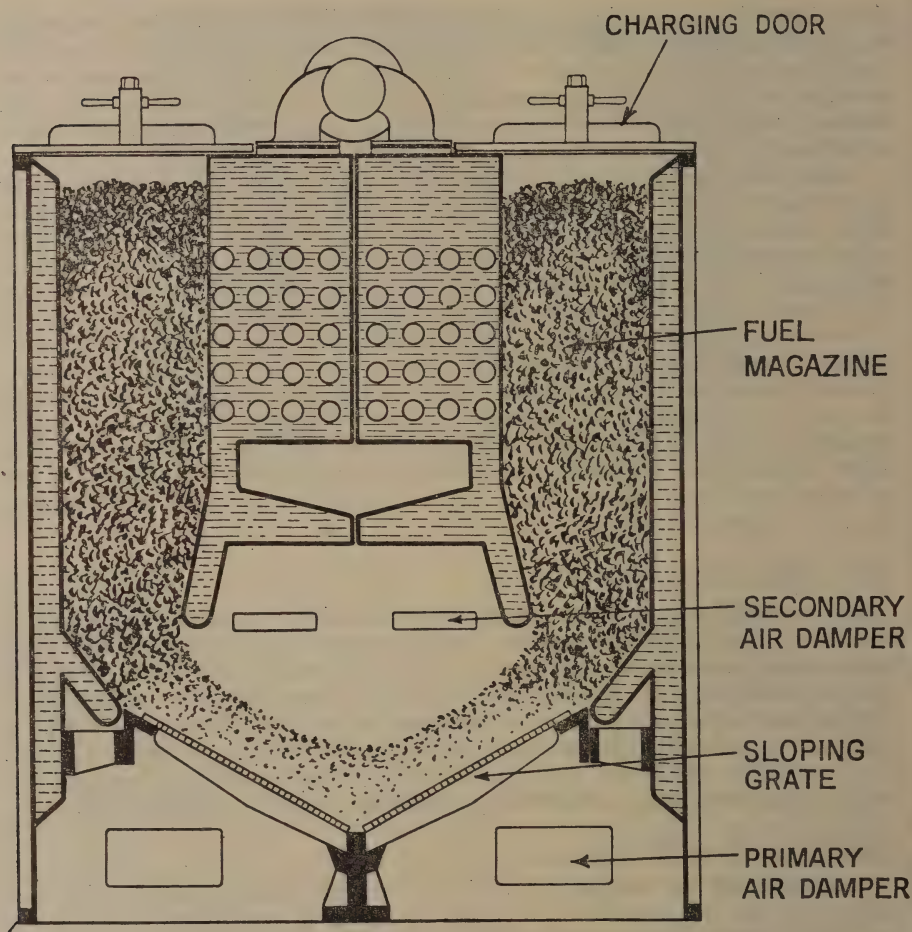


FIG. 10. Gravity feed boiler.

INDEPENDENT WROUGHT IRON AND MILD STEEL BOILERS

This category includes a large variety of types all of which may be used for heating work and range from a boiler made out of mild steel plates and comprising little more than a box with double walls, to the Lancashire and Economic types. All may be used for heating by hot water or steam.

MOUNTINGS FOR HEATING BOILERS

Boilers for low pressure hot water heating are provided with some or all of the following mountings :

Safety valve: This is essential and must be fitted to all boilers. It may be of the deadweight or spring pattern, and should be of the totally enclosed type. The valve consists of an accurately ground disc held on to its seat by a spiral spring or a series of weights. Adjustment is made by varying the pressure exerted by the spring or changing the number and size of the weights. The valve is enclosed in a metal body having an outlet to discharge water if the valve should lift. A pipe should be screwed into this outlet and carried clear of the boiler so that water will be discharged where it will not do any damage. The cover should be held securely in position and a padlock fitted to prevent

interference by an unauthorised person. Testing levers are sometimes fitted.

Thermometer: This may be of mercury-in-glass type, protected by a steel or brass case, or a dial pattern with pointer. The latter is preferable, but in any case it is essential that the thermometer or the dial be easily read by the operator on the firing floor, because the temperature of the water is a guide to rate of firing and adjustment of dampers. The bulb must be properly immersed in the waterway at the top of the boiler or in the flow main. It is also an advantage to have a thermometer on each main return circuit in the boiler house as a guide to the temperature drop through the system; this facilitates the accurate regulation of the various circuits to ensure proper distribution of the water.

Emptying cocks: These are fitted at the lowest point of the boiler and are operated by loose keys. They are used for emptying the system. Sectional boilers may need one on each side, otherwise it may be possible to empty only one half of the boiler. Water should never be drawn off from a heating boiler for cleaning or similar purposes, as it will result in an influx of fresh water to the boiler which will eventually cause damage by corrosion, or by overheating due to deposits of scale.

Altitude Gauge: A Bourdon type pressure gauge calibrated in feet head is used to indicate the head of water on the system. While not absolutely essential it is useful since it can give an indication of any shortage of water that might occur in the system.

Damper Regulator: This is a simple but useful device consisting essentially of a bulb and bellows filled with a liquid, an operating lever and link. The bulb is immersed in the top waterway of the boiler, and changes in the temperature of the boiler water cause changes in volume of the liquid so producing a movement in the bellows. The movement is transmitted to the lever which is linked to the ashpit damper by means of a rod or chain. Thus variations in the temperature of the water in the boiler cause the ashpit damper to open or close, and by this means a reasonably constant water temperature may be maintained. The use of a damper regulator assists in the economical working of the boiler.

Boilers for low pressure steam heating are provided with the following mountings:

Safety valve: Enclosed spring or dead-weight types are used.

Emptying or blow-down cocks.

Pressure gauge, syphon and cock.

One or two water gauges.

Damper Regulator: This is similar to that described for hot water boilers, but operated by steam pressure.

Automatic Boiler Feeder: A device consisting of a float-controlled valve arranged to admit water to the boiler when the water level falls below a certain point. This device is used for boilers working at fairly low pressures, and is fed from an overhead tank, the height of which must be sufficient to produce a static head greater than the pressure in the boiler.

METHODS OF FIRING HEATING BOILERS

HAND FIRING WITH COKE OR COAL

Heating boilers may be hand fired with coal or coke. In the usual types of sectional boiler it is not advisable to hand-fire bituminous coals, as these result in large deposits of soot in the flues. Moreover, these fuels are not so suitable for banking for long periods. It is important to use the correct size of the particular fuel used; the manufacturers' instructions on this should be closely followed.

Sectional heating boilers are designed and rated on the basis of one charge of fuel lasting for six hours when being burned at such a rate that the rated output of the boiler is maintained, leaving sufficient burning fuel at the end of this period to re-kindle the next charge. A boiler can, of course, be forced to some extent beyond its normal rating, but forcing should be avoided as it will reduce the combustion efficiency and shorten the life of the boiler.

When the fuel has burned low in the combustion chamber the dampers are all opened and the fire is thoroughly cleaned out, clinker is removed and the ashes raked out of the ashpit. The boiler is then recharged with fresh fuel. All the doors are now closed and the ashpit and flue dampers kept fully open for a short time until the fresh fuel is alight. The dampers are then set at an intermediate position according to the heating requirements.

If the temperature in the building tends to rise above the required figure the dampers should be closed. Overheating should be guarded against, in the interests of fuel economy. During cold weather the boiler will be refuelled about once every six hours while the building is occupied, but during mild weather less frequently.

It may not be economical in a building occupied every day to let the fire go out each night and to relight again early the following morning, as it may use more fuel than if a banked fire is kept going during the night. In mild weather, if the building is unoccupied during week-ends the boiler may be put out of commission between Saturday morning and Sunday evening, but in cold weather the fire must not be allowed to die out; otherwise, damage by freezing may result.

An average day's firing will comprise cleaning the fire and refuelling about two or more hours before the building is to be occupied, and repeating this procedure again about mid-day. During the afternoon a slower fire will generally be sufficient to maintain the building temperature and this charge of fuel should last until the evening when the fire is again cleaned out and refuelled, the ashpit door and flue dampers now being almost completely closed and the boiler left banked for the night. The secondary air damper should be left open during banked periods to admit additional air over the fire and ensure proper combustion of the gases distilled from the fuel.

The boiler flues should be cleaned out frequently. (See page 658.)

MECHANICAL STOKERS

Mechanical stokers of the underfeed type are often used with sectional heating boilers (Fig. 11). They consist of a steel fuel hopper outside the

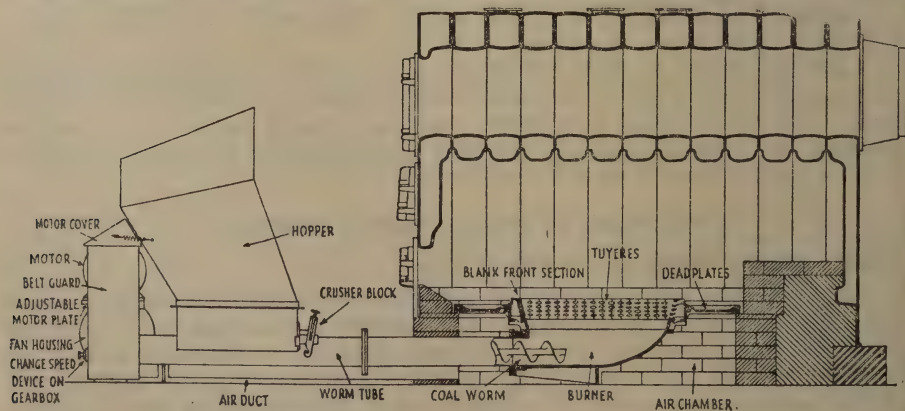


FIG. 11. Underfeed stoker applied to a sectional boiler.

boiler and a retort inside the boiler, the two being connected by coal feed and air supply tubes. Coal is fed into the retort from the hopper by means of a revolving worm in the coal tube driven by an electric motor. The motor also drives a small fan which blows air into the retort through a number of openings, this air assisting in cooling of the retort as well as supporting combustion. The motor is under the control of a pressure switch or thermostat, according to whether the boiler is for steam or hot water. The hopper usually holds six or eight hours' supply of fuel, and may be filled by hand or by chutes from overhead bunkers or by an elevator and conveyor. In suitable cases the mechanical stoker can be arranged to feed the coal directly from a storage bunker at boiler level, and when this arrangement is adopted the fuel hopper is eliminated and the feed worm of the stoker is extended directly into the bunker space.

This type of stoker will burn low-grade coals of small size. A washed fuel is preferable, but not essential. The fuel enters the combustion zone from underneath, the volatile matter is distilled off, passes through the burning fuel above, and is consumed in the space above the fuel bed, so that fuels with high volatile content are burned smokelessly. Much closer control is possible than by hand firing, with consequent reduction in fuel consumption, and a cheaper fuel can generally be burned. Against this, the capital cost of the stoker, repairs and replacements, and the cost of electricity must be considered.

Chain grate stokers are now used with sectional boilers, and mechanical stokers of various types are used on large plants utilizing Lancashire, Economic and similar boilers. They are dealt with in Chapter 11.

PRE-BOILER BURNERS

In this type of burner, the fuel is consumed in a separate furnace fitted at the front of the boiler, and the hot gases produced in the burner are passed into the firebox of the boiler. In a typical case, the burner comprises fuel hopper, water jacketed furnace, and electrically driven fan. The hopper is mounted above the furnace, and fuel falls by gravity from the hopper to the firebed in the furnace. The water space surrounding the furnace is connected by means of flow and return pipes to the water space of the boiler, thus increasing the output from the boiler, and reducing radiation losses from the burner to a minimum. The fan provides primary and secondary air to the

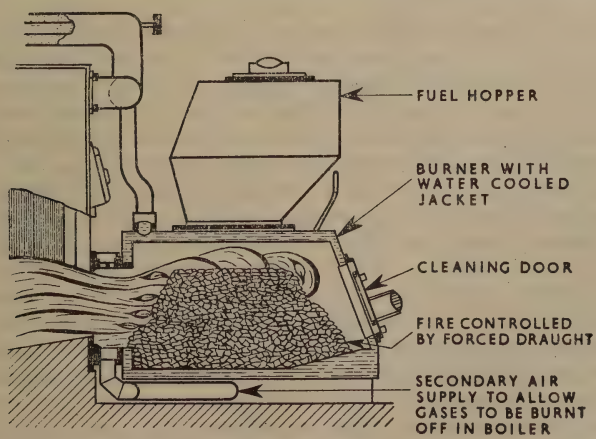


FIG. 12. Pre-boiler burner.

furnace and is controlled by a thermostat or pressurestat. Fig. 12 shows the general arrangement of a pre-boiler burner.

In another type of burner, coke from a hopper is fed by gravity to the fuel bed in a water cooled combustion chamber, and combustion of the fuel is supported by a jet of air discharged downwards on to the surface of the firebed. The water jacket is connected by flow and return pipes to the boiler. The air jet is provided by an electrically operated fan which is controlled by means of a thermostat.

Pre-boiler burners can burn fuels with high efficiency.

GAS FIRING

Gas burners are available for attachment to ordinary sectional boilers. There are also boilers specially designed for burning gas, and other types, incorporating forced draught fans, which burn a gas-air mixture in specially designed chambers or tubes, some with refractory material arranged to extract the maximum amount of heat from the gas before it passes into the chimney. Some of these boilers are highly efficient under close thermostatic control. Various safety precautions are essential to guard against escape of unburned gas due to failure to ignite. Flues also require baffles to guard against effects of wind blowing back into the boiler, and special precautions must be taken to deal with condensation in flues due to the high hydrogen content of coal gas.

OIL FIRING

Oil fuel is being used on an increasing scale for firing central heating boilers and it has many advantages compared with solid fuel. Broadly speaking, the thermal content of oil fuel is about one and a half times that of an equal weight of solid fuel. Oil can be easily atomized and mixed with air so as to yield a high combustion efficiency, and it can be quickly and precisely controlled ensuring that fuel is used only when there is a demand for heat. Because of these factors, oil often displaces more than its thermal equivalent in solid fuel and if the comparison is made with hand fired solid fuel firing, one ton of oil may displace nearly two tons of solid fuel. Thus, if allowance is made for the saving in labour costs which may also result from oil firing, the cost is in many cases attractive compared with solid fuels, although the capital cost of the equipment, and the recurring cost of repairs and maintenance, must be taken into account.

There are many types of oil burners, and in general they comprise a means for introducing oil into the combustion chamber of the boiler in a finely divided or atomized form so that it will readily ignite and burn. Provision is made for ensuring a controlled supply of air to ensure efficient combustion. Oil burners can be fitted to most types of central heating boilers, and they may be arranged for fully automatic, semi-automatic, or manual operation. Fully automatic burners are self-igniting, and work on the on-off principle, generally at a constant rate. Semi-automatic systems are ignited by hand, and thereafter operate continuously with a regulated flame between high and low limits. Hand-operated systems are lit by hand and the burner controls are arranged for hand operation. Automatic controls and protective devices are incorporated depending on the particular system employed. For instance, the fully automatic burner will have an automatic ignition device, a thermostat or pressure switch for starting and stopping the burner and devices for shutting off the oil supply in case of failure of the ignition or of the flame.

Packaged boiler and burner units are also made, in which the boiler and burner are designed and installed as a single unit. For very small installations, oil burners of the vaporizing type are normally used. In these the oil, instead

of being atomized, is vaporized in a vaporizing pot fitted in the combustion chamber of the boiler, and in general they operate on the high and low flame principle.

The heavier and cheaper grades of fuel oil are generally more suitable for larger installations, smaller installations utilizing the lighter and more expensive grades.

The fuel oil is usually stored in tanks outside the boiler house and, depending on the grade of oil employed, arrangements may have to be made for heating the oil in the storage tank and prior to atomizing in the burner. Precautions and regulations to be observed in the storage and use of oil should be carefully studied before using oil fuel, and it is advisable, when installing oil firing arrangements for central heating plants, to observe British Standard 799 "Oil Burning Equipment"⁴, and the code of Practice for Oil Firing Installations and Conversions which, at the time of going to press (1957) is under preparation by the British Standards Institution.

The subject of combustion of oil fuels is dealt with in greater detail in Chapter 13.

CONTROL OF DRAUGHT

The correct control of draught is important if efficient combustion of fuel is to be obtained.

Hand-fired boilers have three dampers, the ashpit damper, the flue damper and the secondary air damper. When the first two are fairly fully open the third is usually nearly closed. These two main dampers control the passage of air through the firebed and consequently the rate of combustion of the fuel, and their setting depends upon the amount of heat required. The secondary air damper controls the admission of the additional air to the combustion space above the fuel bed. Its function is to assist in the complete combustion of the gases rising from the fuel bed. After the fuel is first added to the fire the amount of secondary air required is at its maximum, but as the fuel burns through the secondary air can be reduced.

The use of damper regulators has already been described. Another method of damper control is to have the dampers coupled to small pulling motors which are operated electrically by a thermostat or pressurestat.

In mechanically fired boiler plants the draught is usually produced by a fan or fans, frequently, but not always, under the control of a thermostat or pressurestat. No manual regulation of dampers is then necessary, except that when one boiler on a range is out of use the main damper should be closed to isolate the boiler from the flue.

Changes in wind velocity can cause variations in chimney draught; to offset this a chimney draught stabiliser can be fitted. A stabiliser consists of a balanced flap mounted in a frame built into the side of a flue, usually near the base. The stabiliser is set for normal conditions and any increase of draught due to wind velocity causes the balanced flap to open and admit air directly into the flue, thus maintaining a reasonably constant draught at the smokehood.

Inlets for fresh air must be provided to the boiler house to ensure an adequate supply of air for combustion.

MAINTENANCE AND ATTENTION TO BOILERS

There is sometimes a tendency for a boiler house to be regarded as a place which must inevitably be dirty. A dirty boiler house is probably also an inefficient one, and whatever method of firing is adopted, cleanliness and tidiness are essential. Soot and ash both contain sulphur which, in conjunction with water, produce sulphur acids which are extremely corrosive to metals. The useful life of a boiler may be greatly reduced by dirt and corrosion.

All boiler doors must be kept clean and fit well, door hinges, dampers and operating gear being maintained so as to work freely without sticking.

The floor of the boiler house should not be allowed to harbour ashes and cinders, particularly in contact with the boiler base and the floor should be kept dry. All mountings should be kept clean and in proper working order. The pressure in steam boilers may occasionally be raised until the safety valve blows off as a test to ensure that it is working correctly.

Automatic stokers, pumps and similar apparatus should be given regular attention in accordance with the makers' instructions.

Boiler and pipe lagging should be kept in good repair.

Firebars of the grille pattern require renewal periodically, and a spare set should be in hand for use when required.

The firing and clinker doors usually have a removable lining. This becomes burned and distorted in the course of time and must be renewed.

The water should not be emptied from a hot water system unless absolutely necessary for repairs, etc., as each refilling with fresh water causes additional deposition of scale in hard water districts, or corrosion in soft water districts. No harm is done by leaving the system full of water during the summer months when it is not being used.

When the boiler is shut down at the end of the heating season it should be thoroughly cleaned out; all unburnt fuel, clinker and ash should be removed, and the flues and metal smoke connection to chimney stack cleaned and scraped. Where practicable, the surface of the fire pot and internal flues should then be painted with red lead paint to give protection against corrosion due to condensation. If necessary the chimney should also be cleaned. The inside of the furnace and flues should be examined for traces of corrosion.

While not in use, the boiler should be left with all its doors and dampers fully open so that air can circulate through it to the chimney. This will assist in preventing condensation and so reduce the possibility of corrosion. If the boiler is connected to a common flue to which other boilers in service are connected its dampers must, however, be kept closed to maintain draught.

Before starting up at the beginning of the heating season it should be ascertained that the system is full of water, and accumulations of air should be released through the aircocks and air pipes.

THERMOSTATIC CONTROL

The application of thermostatic control to heating systems can result in considerable fuel economy. The methods of operation and utilization are many and varied, controls being available for operation by electricity, compressed air, water pressure and other means. Some of the ways in which thermostatic control may be applied to space heating are as follows:

- (1) Control of boiler draught.
- (2) Control of boiler fuel feed.
- (3) Control of flow temperature by thermostats placed at key points in the building.
- (4) As in (1), (2) and (3), but with the addition of an external thermostat to anticipate changes in heat demand produced by changing external conditions.
- (5) Individual thermostats in each room controlling the heating surfaces for each room separately.
- (6) Control of heating by warm air by means of thermostats controlling heater batteries and unit heaters.

Thermostatic control is discussed in detail in Chapter 28.

THE ECONOMICAL USE OF FUEL IN CENTRAL HEATING AND HOT WATER SUPPLY INSTALLATIONS

CENTRAL HEATING

In considering how material reductions in the consumption of fuel can be achieved the first question to be asked is whether more warmth is being provided than is necessary. Overheating a building by one degree F., throughout the winter, may cause a waste of fuel of about 5 per cent.

The temperature requirements, the efficiency of the installation and the method of operating the plant are all of importance.

(a) *Temperature of Occupied Rooms*

With low temperature hot water heating the temperature in the rooms should be controlled as far as possible by varying the boiler flow temperature according to outside weather conditions. Where this is impracticable, part of the heating in individual rooms should be turned off according to weather conditions. In rooms having more than one radiator, one or more should be turned off if the room becomes too warm. Windows should not be opened in order to reduce the room temperature; this practice is most wasteful of heat.

(b) *Draughts and Ventilation*

As draughts cause a sensation of cold, they should be prevented, and it is important to ensure that the rate of air-change is not greater than necessary.

To reduce the air-change to the necessary minimum it is profitable to seal up cracks and crevices, to examine the fitting of windows and doors, and to fit draught excluders. It will sometimes be found beneficial to fit simple air-locks to external doors.

(c) *Insulation of Hot Surfaces not used as Heating Surfaces*

A survey should be made to ensure that heat is not wasted owing to the loss of heat from uninsulated hot pipes or surfaces not used as heating surfaces. All insulation should be adequate and kept in good repair.

(d) *Thermal Insulation of Buildings*

Attention should be paid to the possibility of reducing the heat requirements of the whole building by the judicious use of structural insulation, particularly where roof losses are high.

Loss of heat through single-sheeted walls is also high and they should be similarly treated. It is advantageous to provide insulating boards behind radiators on external walls, particularly steam-heated radiators. Ventilated wood floors are also a source of heat loss and should be adequately covered, especially to prevent draughts arising through badly fitting joints.

Detailed information on this subject will be found in the Building Research Station manual¹ on the subject.

(e) *Operation of Boiler and Plant*

Consideration should be given to the regime to be adopted in the operation of the plant. The relative merits of continuous and intermittent heating depend upon a variety of factors, including the nature of the building and the duration of occupancy. A considerable amount of heat has to be provided to heat up a building of substantial construction which has been allowed to become cold, and in such buildings it is advantageous to bank the boiler at night. In buildings of light construction the fire may be let out at night, except in severe weather when there is risk of frost.

The principles of operation of hand-fired central heating boiler plants differ somewhat from those applicable to steam boilers (see Chapter 11), in so far as the former have accommodation in the fire-box for a six to eight hours' fuel charge. For this reason, management of this type of boiler is described in some detail below.

The main supply of air for combustion is from underneath the fuel bed, and

for efficient combustion too much air should not be admitted above the fire, though some secondary air is necessary for the combustion of unburnt gases.

The proper balance is provided when, with a well distributed fuel charge, the air inlets of the ashpit and the apertures in the firing door are both open, but the firing door itself is tightly closed.

The output of the boiler should be regulated by means of the damper in the flue pipe. Excessive chimney pull can be reduced by admitting air direct into the chimney by means of a draught stabilizer (see page 655).

To secure the fullest economy, the depth of the fuel bed should be maintained within the following limits :

<i>Size of fuel</i>	<i>Depth of bed</i>	
	<i>coke</i>	<i>anthracite</i>
1 in. to 2 in.	9 in. to 15 in.	6 in. to 10 in.
Over 2 in.	12 in. to 18 in.	8 in. to 15 in.

The boiler should never be filled to more than three-quarters of the capacity of the fire-box if coke is used, and with anthracite to not more than half capacity. These limits should be observed when banking for the night.

Certain common faults in hand firing of central heating hot water boilers can be avoided if the following recommendations are observed; most of these recommendations apply also to low pressure steam and domestic hot water boilers:

- (1) The fire-door should fit properly and not be opened unnecessarily.
- (2) The boiler output should be controlled as far as possible by using the dampers at the back of the boiler; too much air should not be allowed to enter the boiler as secondary air above the fuel bed.
- (3) Air leakage should be prevented. All likely points, joints, dampers, doors, etc., should be tested periodically with a lighted taper.
- (4) Clinker and ashes should not be allowed to accumulate on the firebars, as they increase the resistance of the fuel bed and cause too much secondary air to be drawn in.
- (5) The fire should not become too hot, since an intense fire destroys the bars, promotes clinker formation and may increase the amount of volatile matter that escapes unburned.
- (6) The fuel must be evenly distributed over the grate bars. It should not be disturbed unnecessarily as this promotes clinker formation. (See Chapters 8 and 11.)
- (7) When the fire has been refuelled or restarted in the morning it should not be left too long unattended. The dampers should be adjusted to suit the demand for heat as soon as the fire has become established.
- (8) The boiler flow temperature should be varied according to the weather, the following figures being a convenient guide:

Outside shade temperature—° F.	55	50	45	40	35	30
Boiler flow temperature—° F.	105	120	135	150	165	180
- (9) It is generally better to bank the fire for the night, or to keep a slow fire, than to force the boiler in the morning. When a fire is to be banked it should not be thin, and the bulk of the fuel should be heated to dull redness before the dampers are adjusted for the night.
- (10) Boiler flues should be cleaned at least twice a week, and more frequently if bituminous coal has to be used; soot and ash prevent the transmission of heat from the flue gas to the water in the boiler. Bituminous coal should not be used in central heating boilers, except in emergency, as it coats the heating surfaces with soot.
- (11) Fuel should be kept dry. Unburnt cinders should be recovered from the clinker and ashes and put back on to the fire.

The general technique of banking and stoking is discussed in Chapter 11.

CENTRAL HOT WATER SERVICE

(a) *Temperature*

Water for baths and hand washing is required at a temperature between 100° and 110° F. The temperature of the secondary flow leaving the storage cylinder should be so adjusted that the temperature of the water at the taps is very little in excess of the above figures, and certainly not more than 120° F. This can usually be attained with a flow temperature of not more than 135° to 140° F. The lower this temperature can be kept the less heat is lost by radiation and convection from the circulation.

Hotter water required in small quantities is best obtained by providing additional heat at the point of use as, for example, for washing greasy dishes. For hotels and hospital kitchens this is usually done by thermostatically controlled calorifiers fed from the hot water service and heated up to the required temperature by steam, gas, or electricity.

(b) *Capacity of Boiler and Storage Vessels*

Boilers should not be forced to meet peak demands and when these are likely to occur storage capacity should be increased, or if this is impossible, the water in the cylinders should be stored at a higher temperature, an automatic mixing valve being provided to limit the temperature of the water in the secondary circulations. The quantity of hot water stored should be sufficient to meet the peak demand, but should not be greatly in excess of this.

If it should be found that even with sufficient storage capacity it is still necessary to force the boiler, then the boiler size is inadequate and must also be increased.

(c) *Loss from Circulating Systems*

In many domestic hot water systems the amount of fuel required to make good the loss of heat from the circulating system accounts for half the total fuel required. Both circulating pipes and storage vessels should therefore be effectively lagged.

Loss may also occur through leaking taps, but the principal loss of heat from the system is generally through water withdrawn for use. Any saving that can be effected in this respect is a positive economy.

COMBINED HEATING AND VENTILATION

The combined heating and ventilation plants previously described (p. 643) were shown as falling into two groups:

Group A Those in which fabric and infiltration losses in the building are offset by heating surfaces situated directly in warmed spaces, and the air for ventilating is introduced at or near room temperature.

Group B Those which heat a building solely by the introduction and distribution of hot air.

A proportion of the air at room temperature is usually recirculated by a fan.

The ventilating plant for both groups consists of an air filter or washer for cleaning the incoming air, a heater battery for warming the air and a fan for passing the air through the filter and heater battery using hot water, steam, electricity, gas, oil or solid fuel, and delivering it through ducts to the distribution points in the heated spaces.

The chief factors affecting the economical operation of combined heating and ventilating plants are:

- (i) The method of working the boiler or heat generating unit and the control of the distribution system serving direct heating surfaces and air heaters.

- (ii) Thermal insulation of hot surfaces not being used for useful heating and insulation of parts of the structures where the heat losses are unduly high.
- (iii) Volume of fresh air introduced by ventilating plant.
- (iv) Temperature of heated spaces and of the air introduced by the ventilation plant.
- (v) Air movement, diffusion and distribution.
- (vi) Re-circulation of warmed air.

These factors are now considered in turn.

Boiler Operation and Insulation

These items are common to all types of heating plants and are dealt with elsewhere. Insulation should be applied to the casing of air heaters and to the ducts in systems of Group B conveying heated air through unheated spaces.

Volume of Air

Two-speed or variable-speed fans may be used to enable more fresh air to be delivered into a building in summer than in winter. The volume of air may also be varied by regulating dampers. Since all the incoming air must be heated in winter, the quantity taken in should be reduced to a minimum, depending on the number of occupants and the working conditions.

Air Temperature

The difference between the internal temperature of a heated space and the external air affects in a direct ratio the quantity of fuel required for heating. To conserve fuel the internal temperature should not be higher than is necessary.

With Group A plants the temperature of the warmed air should not exceed the required temperature of the room.

With Group B plants, since the hot air provides the whole of the heat for the building, a higher air temperature is required in cold weather than in mild weather. Therefore the temperature of the air leaving the heater should be regulated from time to time according to the external temperature to maintain the required temperature in the heated spaces at the working levels.

Most modern combined heating and ventilating plants are equipped with automatic controls operating on the heater batteries. In Group A plants, automatic control ensures that the air is introduced at a steady temperature irrespective of changes in the external temperature. Group B plants should be arranged so that the air temperature is not higher at any time than is necessary to maintain the required internal temperature.

Air Movement

Air movement has a marked influence on sensations of warmth. For winter working, therefore, the volume of fresh air introduced to the plant should be kept to a minimum and also the total volume of air delivered to the rooms should not be so large as to cause excessive air movement.

Local variation in air velocity that generally occurs in heated spaces may be corrected by altering the volume of air by adjustment of the local regulating device, and variations near to an inlet by fixing deflector plates or grilles to break up the air stream and distribute it over a wider area.

The distribution of the hot air in Group B plants has an important bearing on the amount of heat necessary to produce the required temperature at the working level. Except in special circumstances the deflecting louvres or nozzles on the inlet openings should be adjusted so that the air stream is directed towards the working level and does not impinge on any part of the structure, particularly the roof or outer walls, as otherwise the heat loss from the structure is increased.

Regulating dampers at the different outlets should also be adjusted so that

the temperature of the diffused air in the horizontal plane is as uniform as possible.

When adjustment of the regulating dampers does not produce uniformity in the temperature of the diffused air, instead of heating the whole of the air to an unduly high temperature for the sake of one section of the system, a booster heater may be installed in the branch duct serving the particular section, or alternatively local heating surfaces may be provided.

Air Re-circulation

During the heating season, when the need for intake of fresh air is at a minimum, a proportion of air from the heated spaces should be mixed with the fresh air to reduce the load on the air-heating battery, and to conserve fuel.

In Group A plants serving spaces where people are assembled in numbers varying with the occasion, the quantity of re-circulated air will require adjustment, but in plants serving spaces occupied by a regular number of people and in most Group B plants, the quantity of re-circulated air need not be varied.

In plants where no provision for re-circulating the air has been made, consideration should be given to the addition of re-circulation equipment where this is practicable.

REFERENCES

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- ² *A Guide to Current Practice*, 1955. London, Institution of Heating and Ventilating Engineers.
- ³ *Basic Design Temperatures for Space Heating.* Post-War Building Studies No. 33, 1955, H.M.S.O.
- ⁴ B.S. 799, *Oil Burning Equipment.* 1953, London, British Standards Institution.

OTHER REFERENCES

Readers wishing to study the subject in greater detail are referred to the standard text books, advice on the selection of which may be obtained from the Institution of Heating and Ventilating Engineers, London.

CHAPTER 25

DRYING AND CONDITIONING

IN this chapter, drying refers to the removal of a liquid—generally water—from a marketable material by thermal methods, and includes evaporators as, for example, when heat is used to remove large quantities of water from a slurry. It also includes *dehydration*, a special term used for the drying of food-stuffs and other organic or biological products. Under the last heading is included the special technique of drying by freezing methods.

The reasons for drying materials can generally be classified within the following five groups:

- (a) to obtain the material in the form most suitable for processing, or for general use,
- (b) to sterilize and to “condition” material,
- (c) to recover waste products,
- (d) to reduce transport costs,
- (e) to simplify handling.

THEORY OF DRYING

The process of drying a wet solid involves the transfer of heat from the drying air to the liquid in order to cause evaporation and to promote movement both of the internal moisture in the solid and of the evaporated liquid. These actions occur simultaneously and the physical factors controlling their rates determine the rate at which the solid can be dried. The physical factors applicable depend, in turn, upon the method of drying used and the nature of the material, the latter often predominating since many products can be ruined if they are dried too quickly.

INTERNAL MOVEMENT OF MOISTURE

A study of drying is thus concerned with (a) internal movement of moisture and (b) external evaporation of moisture from the surface of a solid. The possible mechanisms of internal liquid flow are as follows: diffusion, capillary flow, flow due to pressure gradient, flow due to shrinkage, flow caused by internal vaporization or condensation and flow due to gravity. The ultimate flow is generally a combination of these mechanisms, one or more of them taking precedence as the drying proceeds.

The internal movement of moisture is obviously a complex subject which will vary with the nature, size and moisture content of the material to be dried. In general, the maximum moisture gradient that can be tolerated without causing damage to the material, or producing surface hardening, determines the rate at which the internal moisture can be removed.

Fundamental knowledge on the internal flow of moisture is scanty; until more is available, the internal movement of moisture during the drying of a material is controlled by setting up external drying conditions that have been found in practice to be the most suitable. The period of time required to dry different materials varies greatly and may range from a fraction of a second to many weeks.

EXTERNAL REMOVAL OF MOISTURE

In drying practice it is the external removal of moisture that is mostly considered, since external conditions are more amenable to measurement and control. The external variables that appreciably affect the drying rate are (a) air temperature, (b) relative humidity, (c) velocity and degree of turbulence,

(d) size of material, (e) agitation and (f) method of contact between any hot surfaces used and the wet material. In many drying problems only some of these variables may have to be considered.

PERIOD OF DRYING

It is convenient, in a study of drying, to divide the drying time into the following three distinct periods: (a) warming-up period, (b) constant rate period and (c) falling rate period. These three periods are indicated in Fig. 1 showing the rate of drying plotted against time of drying.

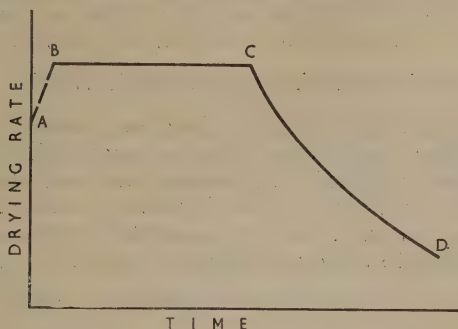


FIG. 1. The periods of drying.

(a) *Warming up period.*

The line AB represents the warming up period, during which the rate of drying increases.

(b) *Constant rate period.*

When a stabilized condition has been reached, the surface moisture is removed at a constant rate, the process continuing until all the surface moisture is removed, as represented by the line BC. The rate of evaporation in this period is independent of the solid and, for the same external conditions, is similar to that from a surface of water. In this case the rate of evaporation is determined by the rate of diffusion of water vapour, through the air film at the surface of the solid, into the drying air stream.

A constant rate of evaporation from the surface of a solid maintains a constant surface temperature which, unless affected by other heat sources, will approximate to the wet-bulb temperature. With additional external heat sources such as by radiation and conduction, the surface temperature will lie between the wet-bulb temperature and the air temperature.

When heat is transferred to the wet solid from a heated surface by conduction and where convection plays only a small part, the boiling-point temperature is the controlling factor in the rate of drying. In such cases, the rate of drying is much greater than the rate of convection drying in which the drying air is at the same temperature as the hot surface.

Radiant heat increases the normal constant rate of drying by raising the surface temperature above the wet-bulb temperature. In the case of infra-red drying, radiant heat is the primary source of heat for drying, but in most cases of drying, radiant heat is secondary to convection or conduction drying.

In convection drying, the constant rate is determined by the rate of diffusion of water vapour through a laminar film at the water surface. The rate of diffusion is proportional to the vapour pressure gradient across the film. For unit thickness of film the gradient is $(P_s - P_v)$, where P_s is the saturation vapour pressure at the temperature of the water surface and P_v is the partial pressure of the vapour in the main air stream. When the air temperature exceeds the

temperature of the water surface, heat will flow from the air stream to the water by diffusion at a rate proportional to the temperature gradient through the laminar film. This gives us the two fundamental equations expressed in typical units, thus:

Evaporation: lb./sec. / sq. ft. in each case.
 Heat: $H_{\text{heat}} = a(t - t_s)$
 lines 5, 6, 7: delete second solidus in each case.
 664 K = evaporation coefficient in lb./sec./sq. ft.
 $(P_s - P_v)$ = vapour pressure difference in in.Hg.
 d = coefficient of heat transfer B.t.u./sec. sq. ft. deg. F.
 t = dry-bulb temperature of the air, deg. F.
 t_s = water surface temperature, deg. F.

EFFECT OF VELOCITY ON RATE OF EVAPORATION

For any given surface temperature and a given relative humidity of the air, the rate of evaporation depends upon the influence which the air velocity has upon the evaporation coefficient K . Measured values of K obtained by a number of investigators over a range of velocity from 3 to 20 ft. per sec., measured at N.T.P. are given in Fig. 2. With the exception of the results obtained by Hine¹, the curves refer to the evaporation of water. The results obtained by

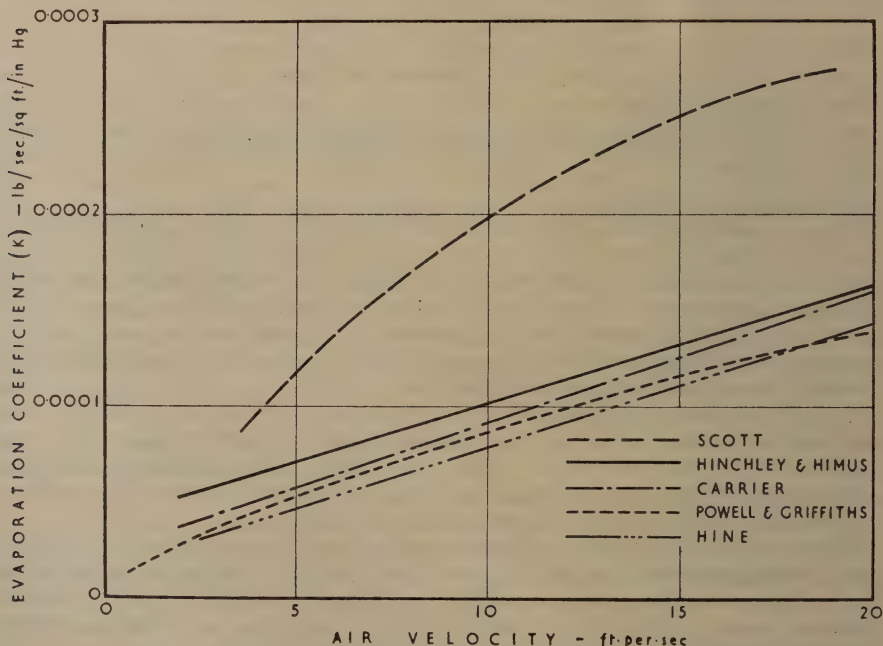


FIG. 2. Influence of Air Velocity on Evaporation Coefficient.

Scott² were from experiments in which water flowed in a film down the inside surface of a vertical tube through which passed a stream of air. The results obtained by Hinchley and Himus³, Carrier⁴, and Powell and Griffiths⁵ were for tangential air flow over a plain water surface or its equivalent. Hine carried out his experiments on a number of organic liquids and the curve shown has been derived from his results.

From Fig. 2 it can be shown that the evaporation coefficient varies as the air velocity to the n th power where n has the value 0.8 to 1.0. The effect of turbulence of the air stream and of the turbulence of the water surface is to increase

the rate of evaporation. High drying rates are obtained with materials which have a large effective surface area exposed to the flow of air.

When the drying air flows in a direction normal to the wetted surface, the influence of velocity varies widely, depending upon the size, shape and nature of the material being dried. Various investigators drying different materials have obtained values of n ranging from 0.4 to 1.4. It is obvious that more precise information is required on the effect of velocity when the air flow is normal to the surface of the material being dried. In the meantime it would appear that an average value for n of 0.8 may be used where specific information is not available.

(c) *Falling rate period.*

When the free surface moisture is removed, the remaining internal moisture must migrate to the surface of the solid before it can be evaporated, and for the same air conditions the rate of drying decreases with reduction of moisture content of the solid. This period during which the rate of evaporation decreases with time is referred to as the *falling-rate* period and is indicated in Fig. 1 by the line CD.

The relative values of the three drying periods vary over a wide range, depending upon the nature of the material. As already stated (p. 662) until the physical laws governing the internal flow of moisture are more completely understood, the conditions and rates of drying must be determined from experience gained in practice.

CRITICAL MOISTURE CONTENT

Referring to Fig. 1 the moisture content at which the constant rate period comes to an end, point C, is referred to as the *critical moisture content* of the material. This varies considerably and is of great importance in problems of drying. For example, if a material is to be dried to a moisture content equal to or greater than the critical moisture content, the whole of the drying process, except for the initial warming up period, will consist of drying under constant rate conditions. On the other hand when drying a material which already has a moisture content below the critical value, the whole of the drying process will lie within the falling rate period.

Some idea of the variation in the critical moisture content of material can be observed by reference to Table 1.

TABLE 1
CRITICAL MOISTURE CONTENT

<i>Material</i>	<i>Critical Moisture Content: per cent. of dry material</i>
Barium nitrate crystals	7
Beaver board	>120
Clay, brick-making	11-14
Carbon pigment	40
Coal	1-14
China clay	16
Kaolin	14
Paper good quality.. .. .	33-41
Paper newsprint	60-100
Sand	3-10
Soap	20
Leather	90-125
Rock salt	7
White lead	11
Whiting	6-12
Wool fabric	30
Wood	40-130

EQUILIBRIUM MOISTURE CONTENT

When a dried material is exposed to a given atmosphere over an extended period it will tend to attain a constant moisture content, referred to as the *equilibrium moisture content*. For any given temperature the equilibrium moisture content will increase with increase of relative humidity of the air. It is common practice to quote the equilibrium moisture content of a material for a given temperature over a range of relative humidity, but more comprehensive information is obtained when the influence of the air temperature is also given.

The moisture content of a material at equilibrium is generally known as the *bound moisture* and any excess is referred to as *free moisture*.

The equilibrium moisture content is of great importance in the storage of foodstuffs which in the dried state and under normal atmospheric conditions are very hygroscopic. This means that the food when dried must be stored under controlled conditions in order to ensure a long life, and in many cases entails storage in sealed containers.

When a dried material is to be stored under normal atmospheric conditions, it is obviously wasteful of heat to dry the material below the equilibrium moisture content corresponding to the air conditions of ultimate storage.

THE PSYCHROMETRIC CHART

In any drying process using air as the drying medium the air serves the dual purpose of providing heat for evaporation of the moisture and of carrying that moisture away. It is therefore essential to know the properties of air: water-vapour mixtures and to have a knowledge of the terms and quantities used before drying calculations can be performed on any specific problem.

The relationship between most of the properties of air: water-vapour mixtures can be expressed graphically in the form of a psychrometric chart, by which drying calculations are greatly simplified.

Dry air, essentially a mixture of oxygen and nitrogen, closely follows the equation for a perfect gas:

$$P_a V_a = RT \quad (1)$$

where P_a = pressure in lb. per square foot absolute
 V_a = volume of 1 lb. of gas in cubic feet
 T = temperature ° F. absolute
 R = a gas constant.

For dry air, R has the value 53.3

Water vapour, however, deviates from compliance with the laws of a perfect gas. When water vapour is mixed with air—as in the atmosphere, or in a drier—it is in the form of superheated steam at low pressure. The lower the pressure and the higher the temperature, the more closely do its properties approach those of a perfect gas. The corresponding equation in this case, adequate for drying calculations, is

$$P_v V_v = R_1 T$$

where P_v = pressure of water vapour: lb. per sq. ft. abs.
 V_v = volume of water vapour: cu. ft.
 T = temperature: ° F. abs.
 R_1 = gas constant

For water vapour, R_1 has the value 85.7.

PARTIAL PRESSURES, SPECIFIC VOLUME AND MOISTURE CONTENT

The total pressure of a mixture of perfect gases is the sum of the respective partial pressures of the individual gases present (Dalton). In a mixture of air and water vapour we have:

$$P = P_a + P_v$$

Where P = total pressure,
 P_a = partial pressure of the air,
 P_v = partial pressure of the water vapour.

For example, if to 1 lb. of dry air W_a lb. of water is added, the pressure exerted by the dry air will drop to P_a , the volume of the mixture increasing in the ratio $P:P_a$.

The volume occupied by the mixture will be the same as the volume that will be occupied by either 1 lb. of dry air at P_a or W_a lb. of water vapour at P_v .

All calculations can be performed by treating the moisture and air separately. The water vapour and the air are linked in calculations only by their common dry bulb temperature and total volume.

The specific volume of dry air is the volume, in cu. ft., occupied by 1 lb. of dry air; this can be calculated for any temperature, from the gas equation. When considering a mixture of air and water vapour, the *apparent specific volume* is generally used; this is the volume, in cu. ft., of that amount of the mixture containing 1 lb. of dry air. The true specific volume of the mixture would be the volume of 1 lb. of the mixture, but in practice this is not so convenient as the apparent specific volume. The true specific volume can be determined by dividing the apparent specific volume by the total weight of the mixture.

$$\text{True specific volume} = \frac{\text{apparent specific volume}}{1 + \text{weight of moisture present}}$$

Firstly consider 1 lb. of dry air at temperature T and pressure P_a , and specific volume V_a cu. ft. per lb.

Secondly consider a mixture of air and water vapour containing 1 lb. of dry air, at partial pressure P_a , and W_a lb. of water vapour at partial pressure P_v , in which the specific volume of the vapour, obtained from the Steam Tables, at P_v and T , is denoted by V_s .

The volume occupied by the mixture is the same as that occupied by *either* 1 lb. of dry air at pressure P_a or W_a lb. of vapour at pressure P_v ; hence

$$V_a = W_a V_s$$

Substituting this for V_a in Equation (1), the equation for a perfect gas, we have

$$W_a = \frac{53.3T}{P_a V_s}$$

Applying the gas equation for water vapour,

$$V_s = 85.7 \times \frac{T}{P_v} \dots \dots \dots (2)$$

From this,

$$W_a = \frac{0.622 P_v}{P_a} \text{ or } \frac{0.622 P_v}{P - P_v}$$

By means of the above equations and the Steam Tables, the relationship between the moisture content of a mixture of air and water vapour and its dew-point for different temperatures and varying relative humidity can be determined. It should be noted that if a mixture of air and water vapour is heated at constant pressure, the partial pressures remain constant, since the weight of water vapour is unchanged.

RELATIVE HUMIDITY AND DEW-POINT

Air can absorb water vapour up to the point where the partial pressure becomes equal to the saturation pressure, P_s , of water vapour (or steam) at the temperature of the mixture. At this point the air is saturated with vapour and the relative humidity is 100 per cent. For unsaturated air the relative humidity

is given as a percentage by the value

$$\frac{P_v}{P_s} \times 100.$$

It is also given by the ratio of the weight of moisture in 1 cu. ft. of mixture to the weight of moisture present in 1 cu. ft. of saturated air at the same temperature.

The dew-point temperature is the temperature at which a given mixture of air and water vapour becomes saturated with water vapour and at which moisture begins to condense out (dew). It may also be expressed as the *saturation temperature* corresponding to the pressure of the water mixed with air. The relationship between the temperature and the pressure may be obtained from the Steam Tables. It should be noted that the dew-point depends only upon the vapour content and remains constant as the mixture is heated. This statement is not necessarily true where other gases are mixed with the air and water vapour.

Psychrometric charts may be constructed to incorporate a wide range of information. The following six properties of air:water-vapour mixtures are generally included:

1. Dry bulb temperature (D.B.T.)
2. Moisture content.
3. Relative humidity (R.H.).
4. Specific volume of moisture.
5. Total heat of mixture (H).
6. Wet bulb temperature (W.B.T.).

A given sample of air is completely specified if *any two* of the first *five* quantities are known; the remaining properties can be calculated or read off directly from the chart, as shown in Fig. 3.

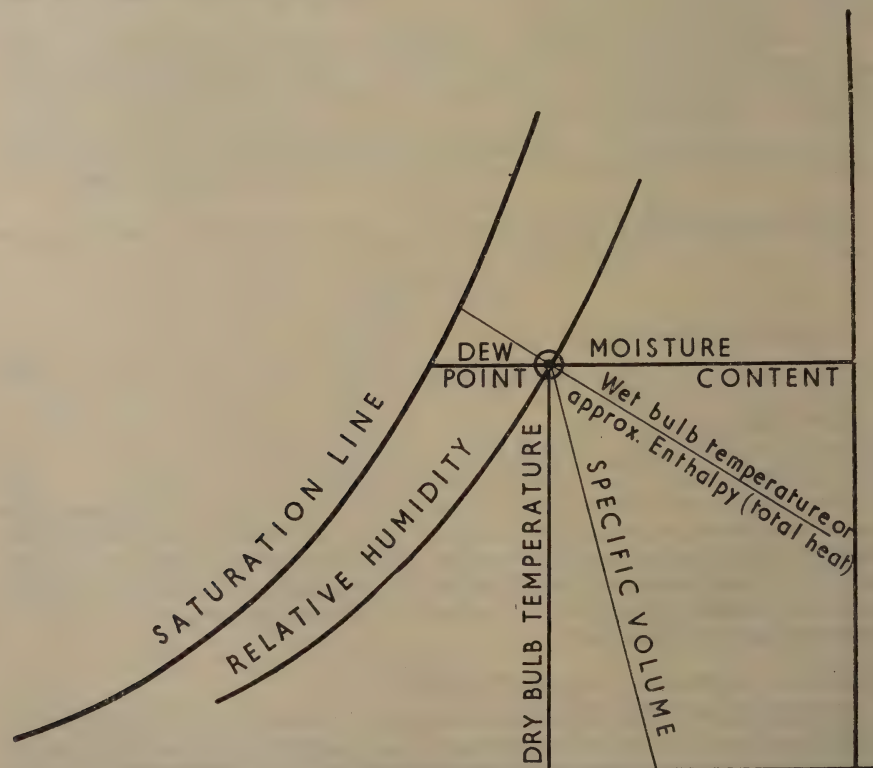


FIG. 3. Psychrometric Chart. (Available Data.)

WET BULB TEMPERATURE

A readily measured property of an air:water-vapour mixture is the wet-bulb temperature. This is the dynamic equilibrium temperature reached by a water surface when exposed to air in such a manner that the sensible heat transferred from the air to the water is equal to the latent heat carried away by evaporation of the water into the air.

The wet-bulb temperature cannot be determined from a simple heat balance for all vapours, but fortunately for mixtures of air and water vapour the wet-bulb temperature is sensibly the same as the temperature of adiabatic saturation.

Fig. 4 is an elementary psychrometric chart using a few of the relationships of the properties of mixtures of air and water vapour. Such a chart can be constructed only for a given pressure—usually the atmospheric pressure 29.92 in. Hg; for any other pressure the readings can be modified by applying the gas laws given earlier.

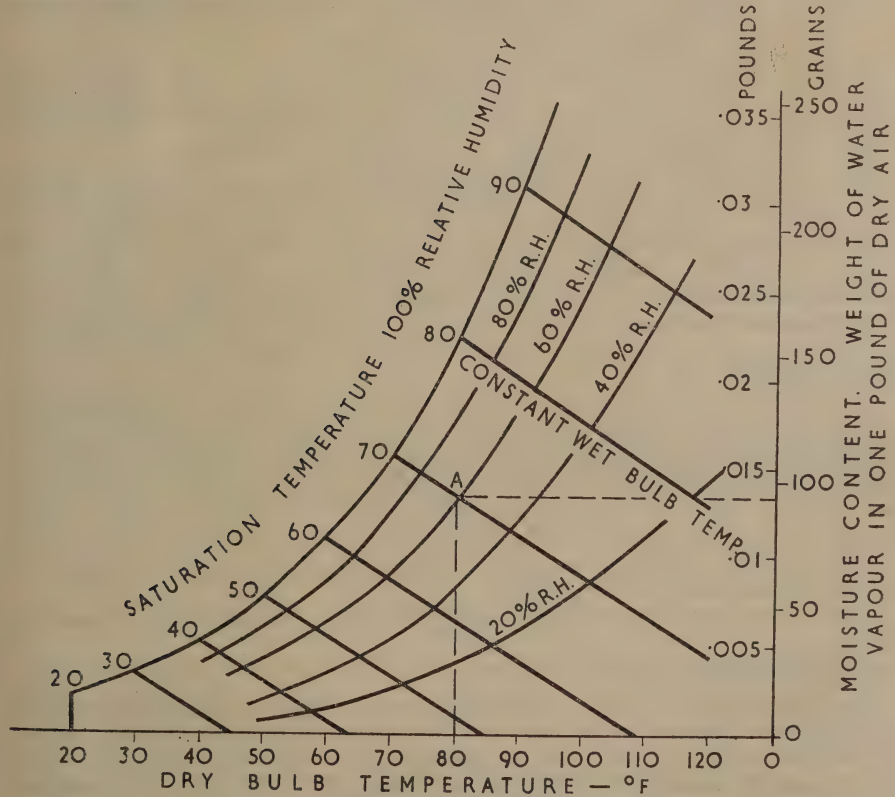


FIG. 4. Psychrometric Chart. Simple Form.

Example: a sample of moist air has a wet-bulb temperature of 70° F. and a dry-bulb temperature of 80° F. Determine the relative humidity and the moisture content.

The sample of air is identified by point A in Fig. 3, where the dry-bulb temperature line at 80° F. crosses the wet-bulb temperature line at 70° F. The relative humidity is then read off as 61 per cent. Similarly the moisture content is read off, on the right-hand scale, as 93.8 grains (0.0134 lb.) per cu. ft. of dry air.

A psychrometric chart of this type is of limited application, since the properties total heat, specific heat and dew-point temperature are omitted.

TOTAL HEAT OR ENTHALPY

The total heat or enthalpy of a mixture of air and water vapour is calculated above an arbitrary base temperature. The temperature for the water vapour is taken as 32° F., thus enabling Steam Tables to be used. For air, however, zero enthalpy is taken at 32° F. or 0° F., the former temperature being normally used in British charts and the latter in American charts. In practice, since only differences in enthalpy are generally considered, the difference due to the base temperature from which it is measured introduces no error; but it would be more logical to use the same base temperature for air and for water vapour for all charts.

The total heat is derived from the formula:

$$H_a = 0.24 (t - 32) + W_a \times H_s$$

where H_a = total heat of moisture, in B.t.u. per lb. of dry air,

0.24 = specific heat of dry air (assumed constant over the normal range of temperatures employed in drying),

W_a = moisture (lb.) per lb. of dry air,

H_s = total heat of steam at its partial pressure, at t ° F., in B.t.u./lb.

The value of H_s for unsaturated air is the sum of (a) the sensible heat, (b) the latent heat, (c) the superheat of the steam in the air.

With saturated air, the steam is not superheated.

The total heat of unsaturated air cannot be conveniently plotted on the chart, since of the three temperatures (a) wet-bulb, (b) dry-bulb, and (c) dew-point, two must be used; this would result in a very complicated chart. In the case of saturated air however, only the air temperature is necessary and since, for moderate differences of wet-bulb and dry-bulb temperatures, there is very little difference between the total heat of saturated air and that of the unsaturated air, the total heat of saturated air is the value plotted in psychrometric charts.

The method used for plotting the lines of total heat varies according to the degree of accuracy required. For many purposes, especially for low temperature psychrometric charts having a maximum dry-bulb temperature of about 120° F., the lines drawn for total heat are taken to be the same as, or parallel to, the lines for wet-bulb temperature, each with its appropriate scale. Where greater accuracy is required, independent lines are drawn for both total heat and wet-bulb temperature; alternatively, additional curves are included from which a correction may be applied.

The chart may then be expanded to include these relationships, as shown in Fig. 5.

HUMID SPECIFIC HEAT

In drying calculations it is often necessary to make use of the specific heat of a mixture of air and water vapour. This is called the *humid specific heat*— C_a —and is the number of B.t.u. necessary to raise the temperature of 1 lb. of dry air and the water— W_1 —it contains, through 1° F. It is generally assumed that the specific heats of dry air and water vapour are constant over the range of temperature used in drying. The sp. ht. of dry air being 0.24 and that for water vapour 0.48, humid specific heat, C_a , = $0.24 + (W_1 \times 0.48)$.

The humid specific heat takes into account both the sensible heat of the air and the sensible heat in the super-heated steam; hence the increase in sensible heat of a mixture is obtained by multiplying the humid specific heat by the number of degrees of rise in temperature.

Psychrometric charts covering the two ranges 0–120° F. and 0–300° F. appear as Plates I and II (between pages 690 and 691).

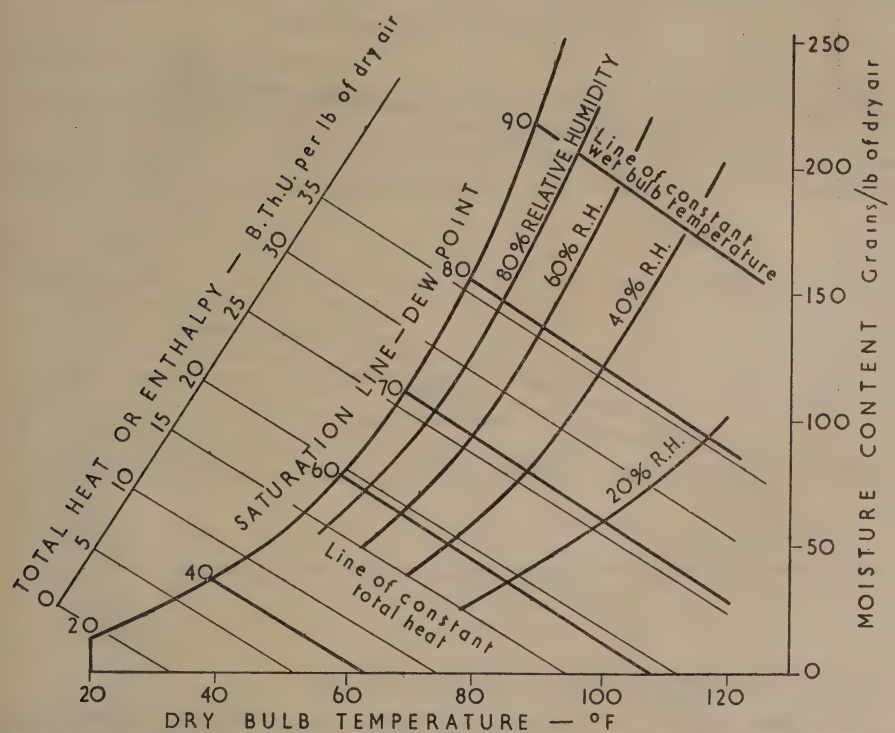


FIG. 5. Psychrometric Chart, showing separate lines of Total Heat above 32° F.

EFFECT OF INITIAL TEMPERATURE OF DRYING AIR ON EFFICIENCY OF DRYING

In order to illustrate the effect of the initial air temperature on the efficiency of a drier, it is convenient to consider an ideal single-stage drier. Theoretical efficiency can be expressed as the ratio

$$\frac{T_1 - T_2}{T_1 - T_a}$$

where T_1 = initial temperature of the air,
 T_2 = exhaust temperature
 T_a = atmospheric air temperature.

In calculations relating to this single-stage drier the following working data are to be assumed:

- (a) Temperature of air at inlet to drier 60° F.
- (b) Relative humidity 50 per cent.
- (c) Drying takes place at constant wet-bulb temperature
- (d) Relative humidity of air leaving the drier 70 per cent.

Using the psychrometric chart for the remaining data, it is possible to calculate the thermal efficiency for any given range of temperatures. The results are plotted in Fig. 6, from which it will be seen that the thermal efficiency increases, at first rapidly and then more slowly as the temperature of the inlet air rises. It is obvious, therefore, that in a single-stage drier it is desirable to operate with as high an air inlet temperature as is practicable, provided that the rate of drying and the temperatures used do not adversely affect the quality of the product.

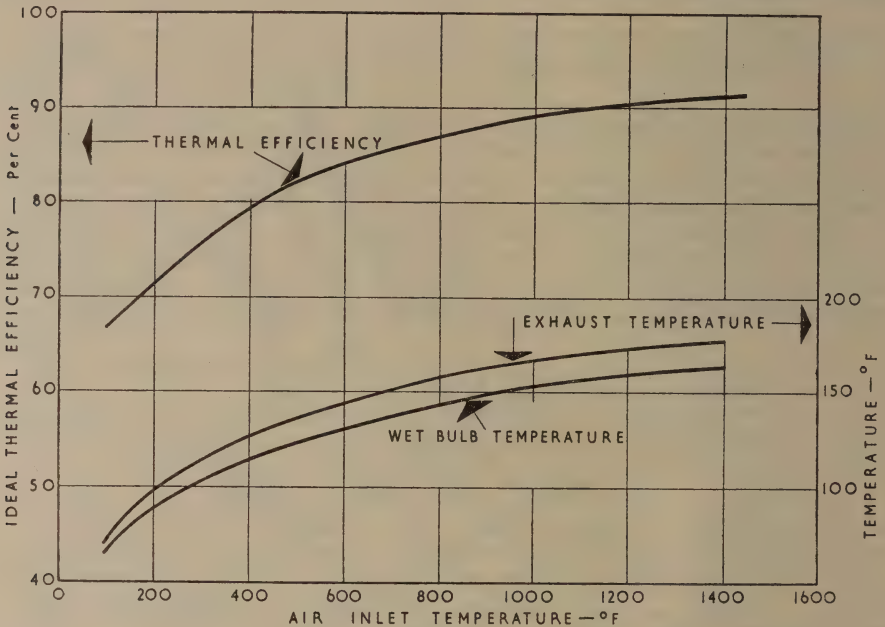


FIG. 6.

EFFECT OF RE-CIRCULATING THE DRYING AIR

With many materials it is not practicable to operate at high air temperatures, and one method of increasing the thermal efficiency which is low because of the low drying temperature, is to re-heat some of the air and re-cycle it through the drier.

Consider a parallel-flow drier with re-circulation, in which W lb. of dry air are re-circulated per lb. of dry air passing through the drier. The thermal efficiency, assuming constant specific heat of the air, may be expressed as follows:

$$\begin{aligned} \text{Efficiency} &= \frac{\text{Heat utilized in drying}}{\text{Heat utilized in drying} + \text{heat rejected in exhaust}} \\ &= \frac{T_1 - T_2}{(T_1 - T_2) + (1 + W)(T_2 - T_s)} \end{aligned}$$

As a practical example consider a drier in which air is supplied to the heater at 60° F. and 50 per cent. relative humidity. The hot air enters the drier at 230° F. and the exhaust temperature is 120° F. From the formula and these conditions, the influence of re-circulation of different proportions of the drying air is as follows:

Conditions of Operation	Thermal Efficiency
No re-circulation	64.7 per cent.
50 per cent. re-circulation.. .. .	78.6 per cent.
80 per cent. re-circulation.. .. .	90.0 per cent.

It should be noted that in addition to increasing the thermal efficiency, re-circulating the air tends to give more uniform drying than with a simple single-stage drier, particularly with batch driers. On the other hand, re-circulating the air gives a smaller mean wet-bulb depression and, for the same dry-bulb temperature and the same air velocity results in a longer drying time.

DRIER DESIGN CALCULATIONS

PARTIAL RE-CIRCULATION

The following notes explain the use of psychrometric charts to obtain data for a single-stage drier operated with partial re-circulation.

Assume that the nature of the material is such that the temperature conditions in the drier are as shown in Fig. 7.

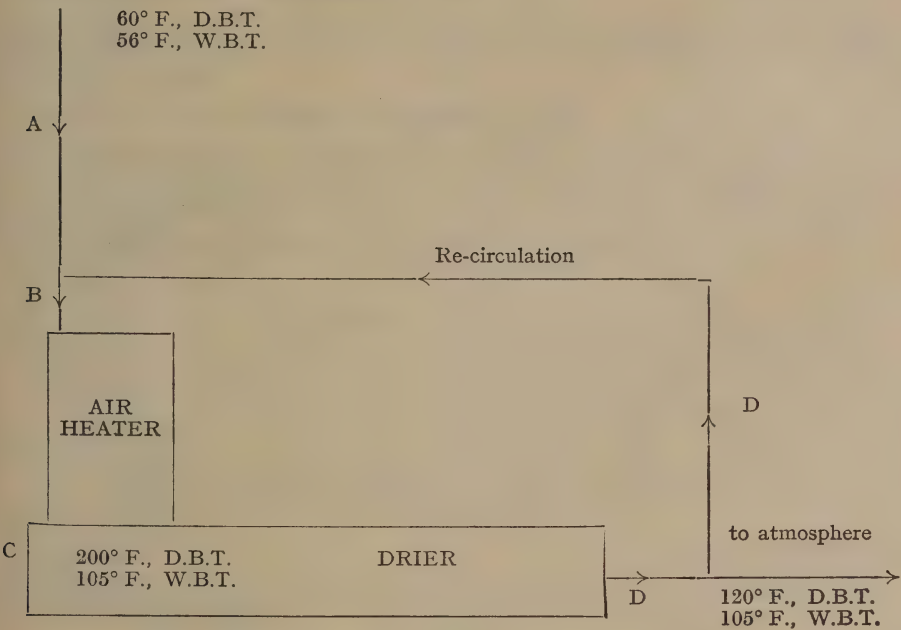


FIG. 7. Single-stage Drier with Re-circulation.

Under the conditions shown the relative humidity of the air leaving the drier is 60 per cent. The wet material is to be dried at the rate of one ton per hour. The initial and final moisture contents are 80 per cent. and 10 per cent. respectively, both expressed on a wet basis.

MOISTURE DISTRIBUTION IN DRIER

Position in drier	Moisture content of material per cent.	Total weight of wet material lb.	Moisture in material lb.	Solids in material lb.
Inlet	80	2,240	1,792	448
Outlet	10	498	49.8	448

DATA FROM PSYCHROMETRIC CHARTS

The observed data from the psychrometric chart are given in Fig. 8.

Moisture in air at inlet to system (A) 60 gr./lb. of air

Moisture in air at exit of drier (D) 330 gr./lb. of air

Moisture picked up in drier (330-60) 270 gr./lb. of air

Moisture to be removed per hour equals 1,792 - 49.8, i.e. 1,742 lb.

Rate of evaporation equals $\frac{1,742}{60} = 29 \text{ lb./min}$

Thus air required equals $\frac{29}{0.0386}$ i.e. 752 lb./min.
 Moisture in mixture of new and
 re-circulated air at (B) and (C) equals 190 gr./lb.

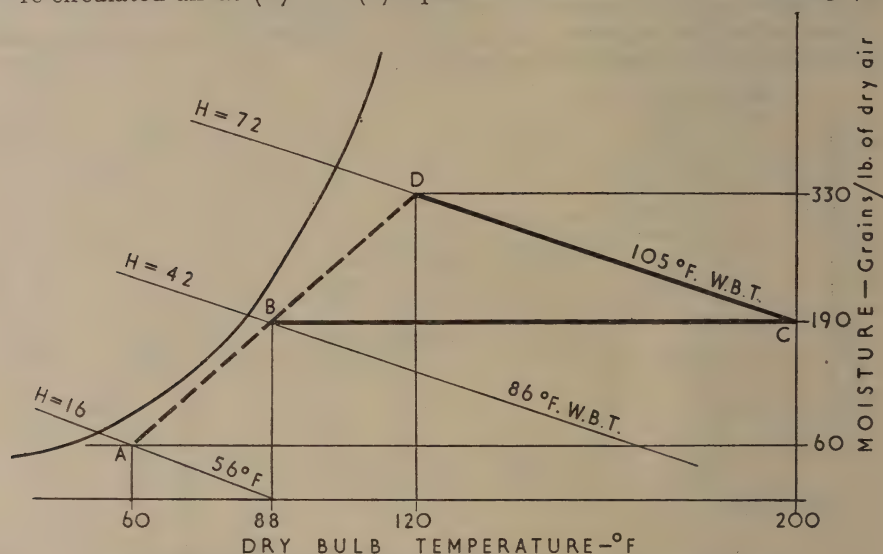


FIG. 8. Psychrometric Chart, for a Single-Stage Drier with partial re-circulation of air.

RE-CIRCULATION

Let W lb. of air be re-circulated per minute. Using a moisture balance:

$$\begin{array}{rcccl} \text{Moisture} & & \text{Moisture in} & & \text{Moisture in} \\ \text{in} & & \text{re-circulated} & = & \text{total air} \\ \text{new air} & \text{plus} & \text{air} & & \text{passing to drier} \\ (752 \times 60) & + & (W \times 330) & = & (752 + W) \times 190 \end{array}$$

Therefore $W = 695$ lb./min.

Hence: total weight of air passing
 through the drier = $(752 + 695)$ i.e. 1,447 lb./min.

HEAT REQUIREMENTS

1,447 lb. per min. at (B) are heated, in the heater, to the condition at (C). Referring to Fig. 8, point B is at the intersection of the line AD with the *constant moisture* line BC.

Total heat per lb. at point C	..	..	..	72 B.t.u.
" " " " B.	..	..	..	42 B.t.u.
Increase in heat in heater	..	..	..	30 B.t.u.
Therefore heater capacity equals $1,447 \times 30$				
i.e. heat to be supplied by the heater	..	..	..	43,410 B.t.u./min.
Temperature of air at inlet to heater	..	..	..	88° F.
" " " " drier	..	..	..	200° F.

THERMAL EFFICIENCY IN DRYING

The thermal efficiency may be regarded as the ratio of the heat usefully employed in drying to the total heat supplied to the drier. Assume that no losses of heat have occurred.

Thermal efficiency equals:

$$= \frac{1,447 (200 - 120) \times \text{humid sp. ht.}}{1,447 (72 - 42)} \\ = \frac{80 \times (0.24 + 0.48 \times 190 \div 7,000)}{30}$$

i.e. 67.5 per cent.

In the above examples the quantities of air have been given in pounds; where they are required on a volume basis the specific volumes may be read from the psychrometric chart.

TYPES OF DRYING PLANT

Many types of plant are made for drying different classes of materials. In general, the wide variety of types is due to the difference in the nature of the material to be dried, but in many cases there is still a wide choice of drying plant for drying a particular material.

Types of drying plant may be classified as follows:

Convection Driers.

Drying rooms and chambers.

Tray driers.

Conveyors.

Tunnel driers with wheeled trucks.

Rotary driers.

Vertical cylindrical driers.

Spray driers.

Pneumatic driers.

Air-swept rotary mills.

Contact Driers.

Flat surface.

Film or roller.

Vacuum Driers.

Freeze Driers.

Radiant Heat Driers.

High-Frequency Driers.

DRYING ROOMS AND CHAMBERS

A simple method of drying is to place the material to be dried in a room or chamber through which hot air is circulated. This method is particularly applicable to the drying of large bodies such as building slabs, bricks, wall board, fibre board, clothes, foundry cores and so forth.

The material to be dried is symmetrically stacked in the drying room or otherwise so placed that the maximum surface of each piece is exposed for drying; it may also be stacked on wheeled trucks.

Hot air is circulated through ducting suitably arranged in the building, with outlets to discharge the hot drying air or gases uniformly over the surfaces of the material being dried. To obtain maximum thermal efficiency the hot air, after circulating through the room, is drawn off, re-heated and re-circulated by the furnace and fan. Humidity is controlled by letting a proportion of moist air escape and admitting new air in its place.

For efficient drying it is essential that all material be subjected to uniform hot gas flow and temperature.

Fig. 9 shows an arrangement of a drying room. Hot air or gases from a heater discharged by a fan to a duct running through the centre of the building, are uniformly discharged over the whole floor of the building. In addition, overhead circulating fans are sometimes fitted to give more uniform distribution of the hot air. It is usual to maintain a fixed drying temperature, and to control humidity in the drying room by exhaust ventilator or by re-heating and re-circulating a part of the air in the chamber.

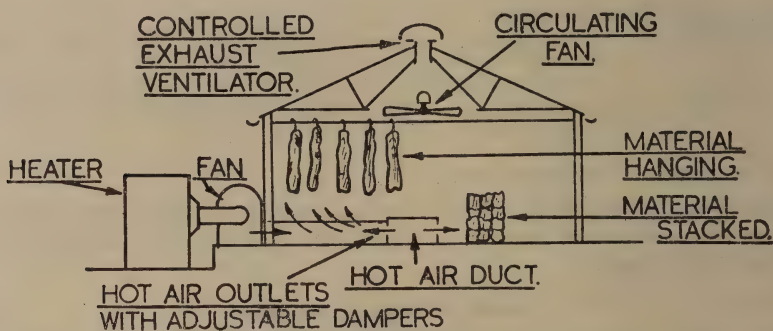


FIG. 9. Chamber drier.

The material to be dried may be either suspended from hooks or suitably stacked to ensure uniform flow of hot air around all its surfaces.

TRAY DRIERS

This is a method for drying small goods, such as small foundry cores, colours, chemicals, food products, etc. The hot gases pass upwards through the perforated bottoms of the trays and through the material, or pass to and fro over the trays.

The trays sometimes slide into racks in a drying chamber or, for convenience in handling, they may fit into racks in a trolley which is pushed into the drying chamber. The system of hot gas ducting, and re-circulation and control of humidity is similar to that for chamber drying already described.



FIG. 10. Simple tray drier.

Fig. 10 shows the simplest type of tray drier. Hot gases from a furnace or heater are discharged by fan into a space below the trays. The hot gases pass upwards through the perforated trays and through the material. With this simple form of drier the efficiency is low, because towards the end of the drying period the hot gases take up very little moisture. Consequently they leave the material at a very low degree of humidity. A more efficient form of simple tray

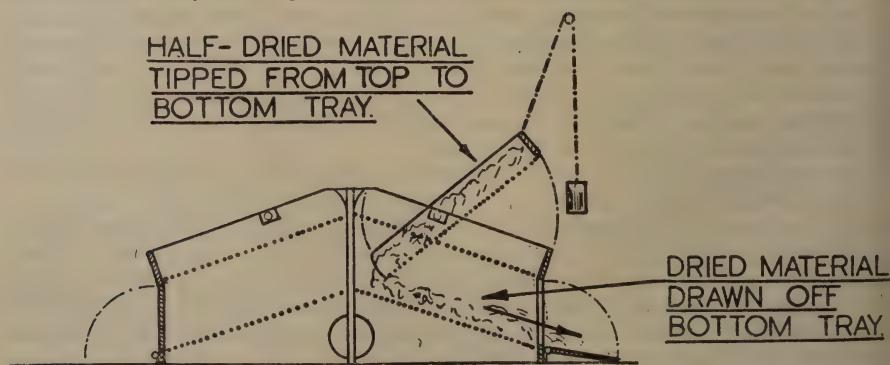


FIG. 11. Simple double-tray drier.

drier comprises two or more superimposed trays (see Fig. 11). The material can be half-dried on the top trays and then tipped on to the bottom tray, the upper one being refilled with fresh material. The drying gases thus leave the top tray at a much higher degree of humidity than in a single-tray drier.

CONVEYOR DRIERS

These comprise a conveyor open or partly open to the atmosphere above, or completely enclosed in a tunnel. The material to be dried passes on the conveyor, through the tunnel. The hot drying gases may flow from end to end of the drier, or upwards and downwards through perforations in the conveyor and thus through the material.

Conveyors are made either of woven wire, or of sections of perforated metal attached to link chains on each side of the conveyor. Sometimes the conveyor comprises a fixed perforated plate over which the material is dragged by drag-bars fixed to moving chains on either side of the conveyor.

Some conveyor driers comprise multiple conveyors, one over another, the material to be dried being fed on to the top conveyor and passing from conveyor to conveyor down the drier.

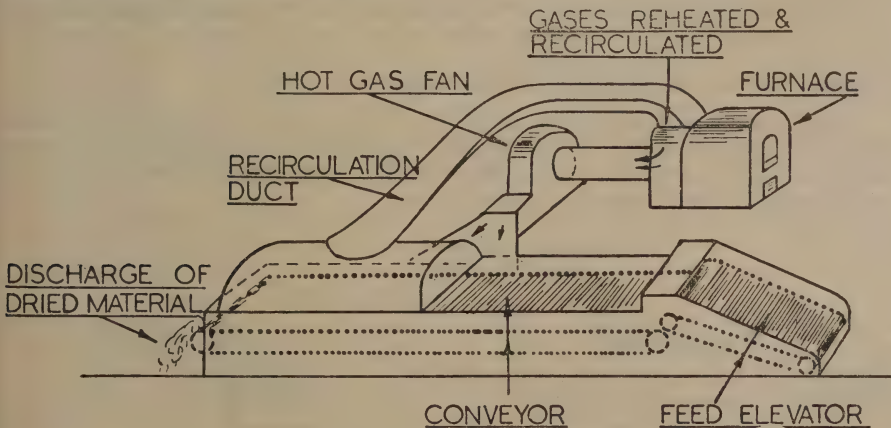


FIG. 12. Conveyor drier.

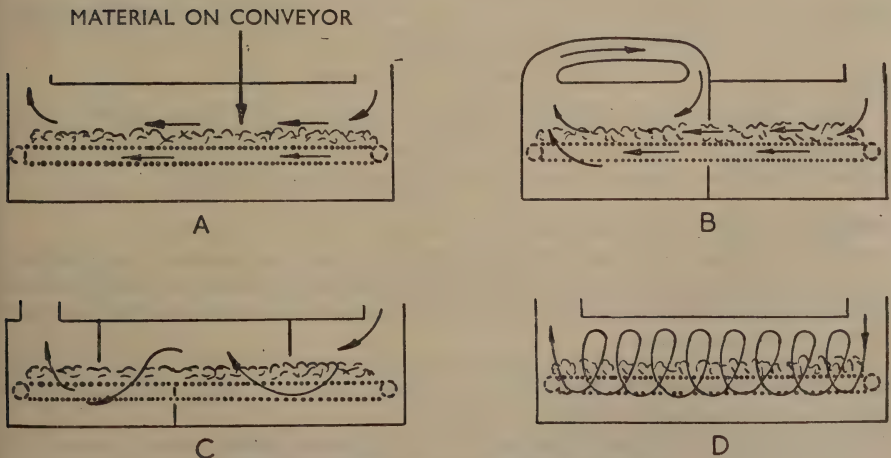


FIG. 13. Gas flow through tunnel driers.

Fig. 12 shows a semi-open conveyor. This differs from those in which the conveyor passes through a tunnel. It is designed to dry goods of high moisture content (76–80 per cent.). The material is spread out on the feed elevator in a layer of uniform thickness and discharged on to the conveyor. In the first half of its passage along the drier, hot gases pass through the material and are discharged at a high degree of humidity. In the second half, the gases leave the material at a much lower degree of humidity and are collected in the hood and re-circulated by the fans, through a re-heater.

In other types of tunnel conveyor driers, the hot gases are circulated over and through material in various ways, as shown in Fig. 13.

In this figure,

- (A) shows the flow of hot gases above and below the material from end to end of the tunnel;
- (B) shows the flow above and below the material in the second stage of drying and re-circulated in the first stage;
- (c) shows hot gases passing up and down through the material as they flow from end to end of the drier;
- (D) shows hot gases passing upwards through the material, and then being drawn down side ducts in the drier and forced upwards again through the material in its passage from end to end of the drier.

TUNNEL DRIER WITH WHEELED TRUCKS

This is somewhat similar to the conveyor driers, but the material to be dried passes through the tunnel on wheeled trucks. When the material on one truck becomes dry, it is pulled out. The other trucks are then pushed forward, a fresh truck being pushed in at the opposite end.

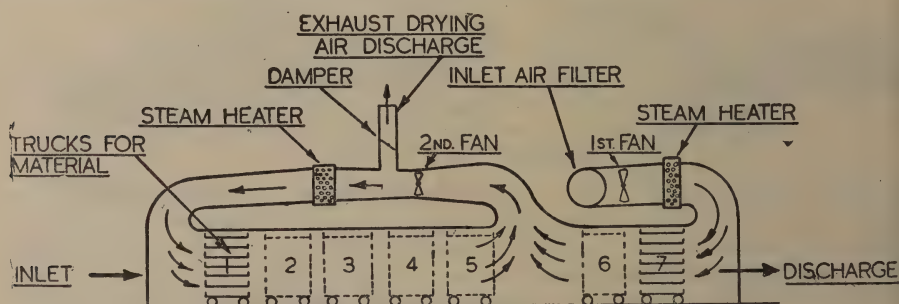


FIG. 14. Tunnel drier for wheeled trucks.

The hot drying gases generally flow from end to end of the tunnel and pass over the material, which is stacked or spread out on trays on the trucks. Alternatively, the hot gases may be circulated as shown in Fig. 14.

SIMPLE ROTARY DRIERS

These comprise a horizontal rotating cylinder with a number of longitudinal shelves or lifting flights inside it (Fig. 15). The smallest driers of this type have cylinders about 6 feet long by 2 feet in diameter and the largest, 70 feet long and 8 feet in diameter.

Rotary driers are used for drying material that has to be turned or tumbled over and over in the hot gas stream to ensure uniformity of drying. Hot gases are generally drawn through the cylinder by a fan.

The material to be dried is fed into the cylinder and falls to the bottom. It is picked up by the shelves as the cylinder revolves and is spilled off, falling

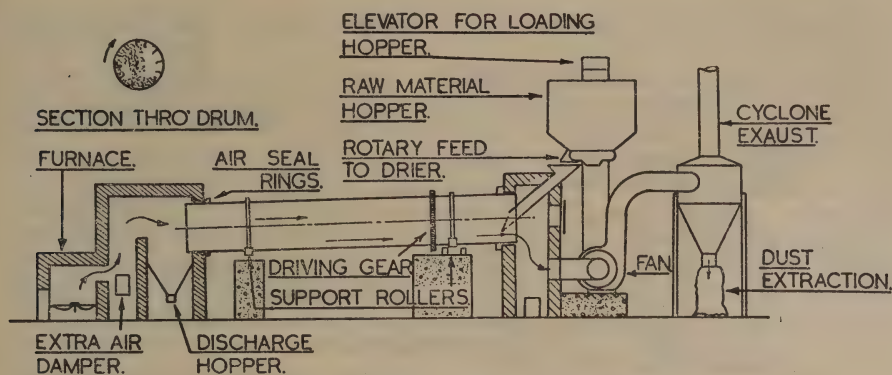


FIG. 15. Single shell rotary drier.

through the stream of hot gases passing through the cylinder. This constant movement of material in the hot gas stream results in uniformity of drying.

The drum is usually set at a slight inclination towards the outlet. The inclination may vary from 1 in 16 for quick drying substances to 1 in 30 or 1 in 40 for slow drying. The inclination of the drum, shape, width, number and form of the shelves or lifting flights, are determined by experience to produce the best showering effect and rate of feed of the material through the stream of hot gases. Spiral lifters are sometimes fitted at the feed end of the drier to propel the material well into the cylinder and prevent spillage over the end of the drum.

These driers are used for drying sticky material such as clay, material that is in fairly large lumps, and also for chemicals and a variety of other goods. Where possible the material is fed into the drier in the direction opposite to that of the flow of hot gases.

It is not possible to use the contra-flow principle when drying materials that are very light or powdery when dry. Such material is usually passed through the drier in the same direction as the flow of hot gases and there is an advantage in this, in that the part of the material which dries quickest becomes lighter and is, therefore, carried through the drier by the hot gas stream quicker than the moister material; this automatically assists in uniformity of drying. The rate of feed through the drum is controlled by the speed of hot gases, by sloping the cylinder down to the outlet end and by sloping the shelves to feed the material more rapidly to the outlet as necessary.

These driers evaporate about 2-2½ lb. of water per cubic foot of cylinder volume per hour and operate at inlet hot gas temperatures of 800°-1,500° F. and outlet temperatures of 250°-450° F.

ROTARY DRIERS—DOUBLE SHELL

In this type of drier the hot gases pass through a central tube and return through the annular space between the inner and outer drums and are exhausted by an induced draught fan (see Fig. 16).

Lifting shelves or flights are fitted inside the outer drum and also outside the central tube.

Hot gases enter the inner tube at a temperature of 1,000°-1,500° F., and a greater part of the heat is imparted to the material through the surface of the inner tube. The material is generally fed into the annular space at the furnace end of the drier. The lifting shelves or flights pick up the material and shower it on to the shelves on the hot inner tube. The material is carried round about

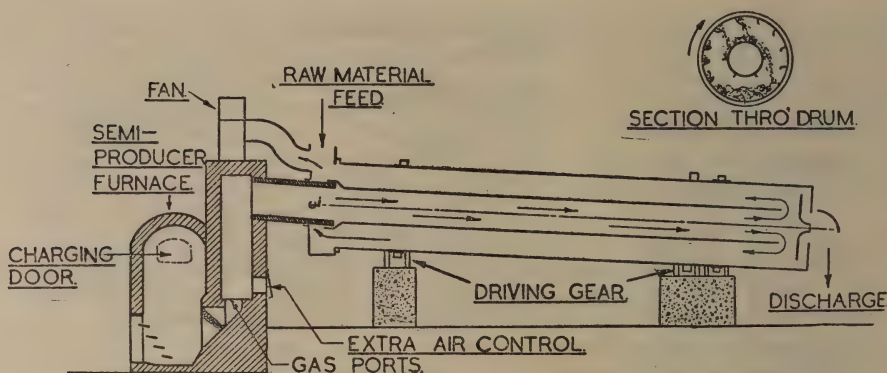


FIG. 16. Double shell rotary drier.

half a revolution on these shelves, during which time it is heated by contact with the hot surface of the inner drum and is then showered off into the outer shell and the operation is repeated over and over again, as the material works its way to the discharge end of the drier.

In another type of double shell drier, the material (usually light material) is fed into the hot end of the inner tube and passes through the inner tube and back through the annular space between the outer shell and inner tube.

Double shell driers generally have a much higher thermal efficiency than simple shell rotary driers.

These driers evaporate $4\frac{1}{2}$ lb. of water per cubic foot of cylinder volume per hour at inlet gas temperatures of $1,000^{\circ}$ – $1,500^{\circ}$ F. The gases leave the inner tube at approximately 400° – 500° F., and are discharged from the drier at about 150° F.

SPECIAL TYPES OF ROTARY DRIERS

There are various proprietary types of high efficiency rotary driers. One type consists of a horizontal drum with a series of internal channels near the circumference into which hot gases are admitted from a fan. The hot air can pass from these channels through louvres to the inside of the drum, the louvres being so

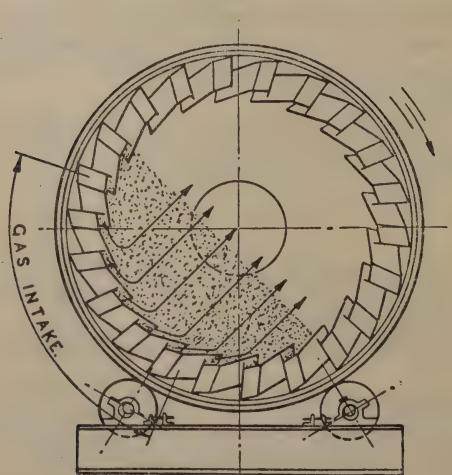


FIG. 17. Louvre rotary drier.

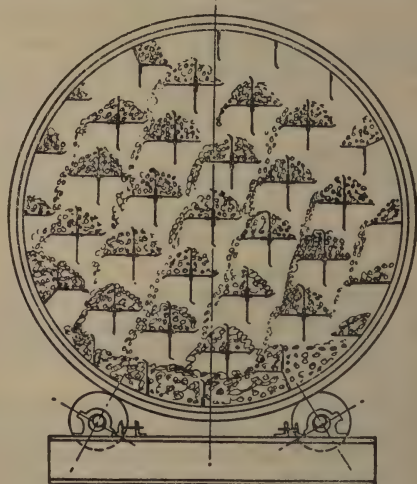


FIG. 18. Cruciform rotary drier.

shaped that the material inside the drum cannot spill back through them (Fig. 17).

This drier generally operates at inlet hot gas temperatures of 750° – $1,000^{\circ}$ F. The material to be dried is fed into the drum, mounts one side of the drum and rolls and tumbles over as it reaches its angle of repose. The hot drying gases are forced through the material as it tumbles over and over.

Another type consists of a horizontal drum with a large number of cross-shaped shelves (Fig. 18). The material to be dried is continually spilling from one shelf to another and is turned over four times in each revolution of the drum, thus ensuring uniformity of drying. In these proprietary types of drier the continuous and uniform tumbling over of the material ensures uniformity of drying and these driers have an evaporative capacity of 6–12 lb. of water per cubic foot of cylinder volume per hour.

VERTICAL CYLINDRICAL DRIERS

Inside a vertical cylindrical casing are a number of concentric rings or shelves. The material to be dried is fed on to the top shelf and is pushed round and turned over at the same time by a revolving rake or scraper. When the material has moved round once, it falls through a gap in the concentric shelf on to the shelf below. Alternatively, the concentric shelves are fixed to a central

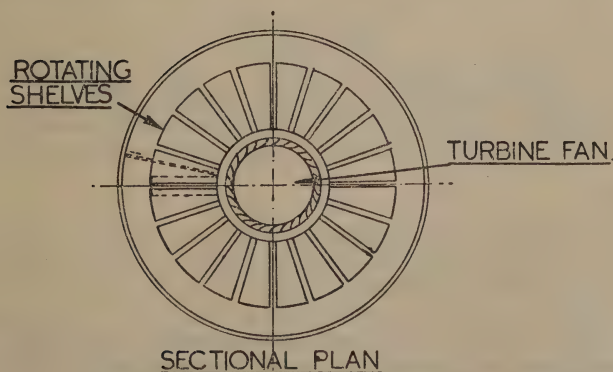
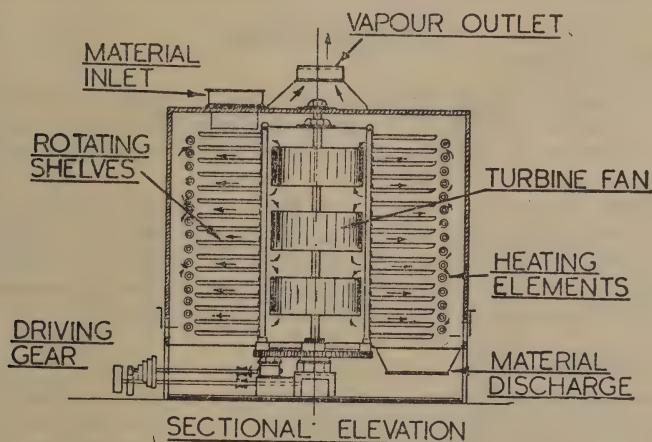


FIG. 19. Vertical cylindrical drier.

spindle and revolve and the material is turned over by a fixed rake.

The flow of hot gases is usually outward over one tray and inward over the next.

Fig. 19 shows a drier of this type. The material to be dried is fed on to and spread over the top tray. The trays revolve and at every revolution the rake or scraper moves the material through a slot in the tray so that it falls on to the tray below. There are three fans on a central vertical spindle and these draw air inwards over the trays below and discharge it outwards over the trays opposite the fans, so that air passes to and fro over the trays from the bottom to the top of the drier, i.e. in contra-flow to the passage of material down the drier.

It will be noted that there are concentric steam coils outside the trays. These serve the purpose of heating and re-heating the air in its passage to and fro over the trays. The heating capacity of these steam coils can be adjusted to give the best air temperature conditions. The fresh material can generally be subjected to a higher temperature than the drier material leaving the drier, and in such cases the capacity of the steam coils would increase the temperature of the air as it flows to and fro and upwards through the drier.

This type of drier is generally used for materials that have to be turned over during drying, and that need a moderately long period of drying. They are also used for slurries and pastes as well as for solid materials.

CONTACT DRIERS

FLAT SURFACE DRIER

A typical example of a stationary flat surface drier is seen in the drying floors used in the china clay industry. Driers of this type are heated from below by hot flue gas from a special furnace or by waste gases from a neighbouring furnace or kiln.

In the drying of veneer the stock is dried between two heated plates. The upper plates are lifted off the stock at intervals of time to enable intermittent conveyance of the veneer through the machine to take place. When the two heated plates make contact with the veneer a high rate of evaporation results, and the pressure of the plates prevents distortion.

FILM OR ROLLER DRIER

This type of drier is used for drying liquids and pasty or pulpy material. Many of these substances exist in a colloidal state in suspension or as emulsions or gels and include milk, pulped potatoes, yeast, starch, blood, gelatine, glue, chemicals, tannin.

The material is fed or extruded on to a steam-heated revolving cylinder. Drying is completed in one-half or three-fourths of a revolution of the steam cylinder. The material is then stripped off in the form of a thin sheet, or breaks up into flakes or powder. For satisfactory operation it is essential that a film of uniform thickness be spread on to the steam-heated drum. The drum is, therefore, accurately machined and ground and a roller feeding arrangement may be fitted. Film driers are made with either single or twin rollers (Fig. 20).

SPRAY DRIER

This is an alternative to the film drier for drying liquid and semi-liquid substances. As its name implies, the substance to be dried is sprayed into a chamber through which pass hot gases.

The total surface of the many particles in the spray is very large; this, together with the movement of the particles, provides ideal conditions for rapid drying. Drying gases can enter the drier at comparatively high temperatures, because very quick rate of evaporation and heat absorption causes a very rapid

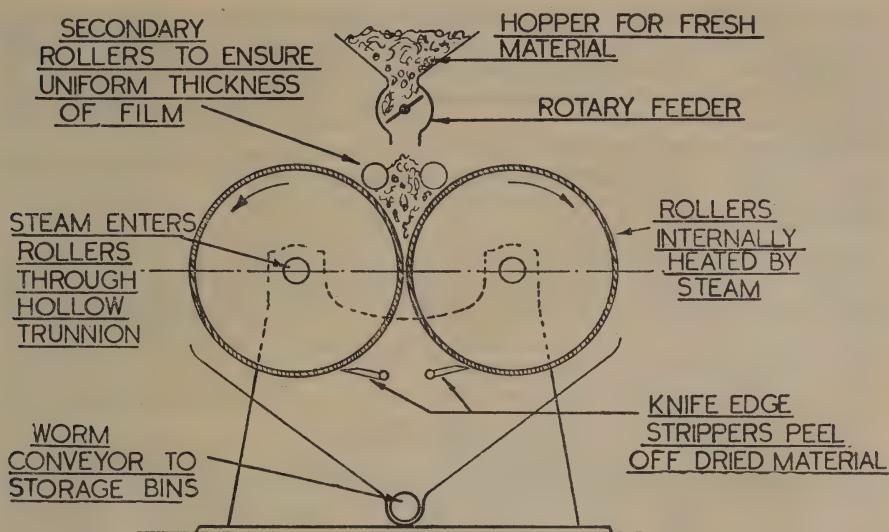


FIG. 20. Film drier.

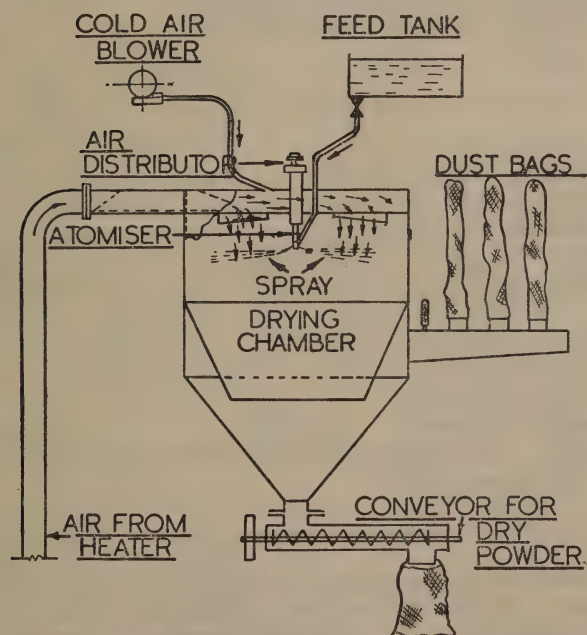


FIG. 21. Spray drying system.

fall in temperature, so that the substance being dried does not rise to a harmful temperature.

The heavier dried particles fall to the bottom of the chamber, the lighter particles being carried over in the exhaust gases and collected in a dust collector, generally of the filter type.

To obtain satisfactory results with spray driers, it is essential that the substance be sprayed as globules of more or less uniform size, otherwise drying will not be uniform. To prevent drying before the atomized particles are sufficiently dispersed, a cold air duct surrounds the spray or atomizer itself. This type of drier is shown in Fig. 21.

Spray driers are used for drying milk, eggs, meat and vegetable extracts and other foodstuffs, and a great variety of chemicals.

PNEUMATIC DRIERS

This is a type of drier used for drying chemicals and other materials in small pieces of uniform size. Basically, this is the simplest of any type of drier. The main element is a vertical tube 30 feet or more in height. Hot gases flow upwards through the tube and the material to be dried is fed in at the bottom. The upward velocity of the hot gases is such that the fresh, moist, heavy material remains almost suspended, whereas the dry material, being lighter, is carried up more rapidly to the discharge outlet.

A drier of this type is shown in Fig. 22. The hot gases from the furnace are induced upwards through the first vertical pneumatic tube, flow down through a second tube and then up through a third to two cyclones with a fan between them. Any undried and therefore heavy material entering the first cyclone falls to the bottom through a discharge pipe and is picked up by a fan and re-circulated through the third pneumatic uptake tube and so re-dried. From the second cyclone the hot drying exhaust gases are discharged upwards and the dried material is separated and discharged for bagging.

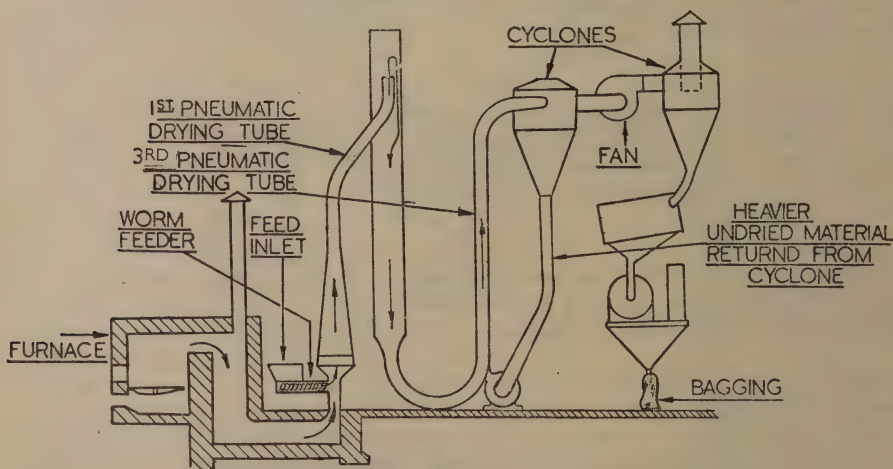


FIG. 22. Pneumatic drier.

Some pneumatic driers incorporate a rotary drier for final drying after the material leaves the second cyclone. The tumbling in the rotary drier improves uniformity of drying.

The simpler forms of pneumatic driers are used for drying chemicals and the type of drier described is used on the Continent (Europe) for drying chaffed dried grass for cattle feeding and for drying coal slurry.

AIR-SWEPT ROTARY MILLS

Some materials require to be pulverized and dried, and these two processes can be carried out in one operation.

An example is the preparation of agricultural lime or whiting from chalk. Chalk or carbonate of lime as quarried is partly in lumps three inches or more in size but also contains fines and powder. Agricultural lime can be dried in various types of driers and the large lumps are broken down in the drying process, but air-swept mills are sometimes used.

Another example is the production of pulverized fuel, where it is necessary for the fuel to be pulverized and dried simultaneously.

Fig. 23 shows an arrangement of an air-swept rotary ball mill, which pulverizes the material while a continuous stream of hot gases passes through the mill and dries and carries away the pulverized material. The hot gases are drawn through the mill by an induced draught fan and the powdered or pulverized material is separated from the hot gases in a cyclone or other type of separating device.

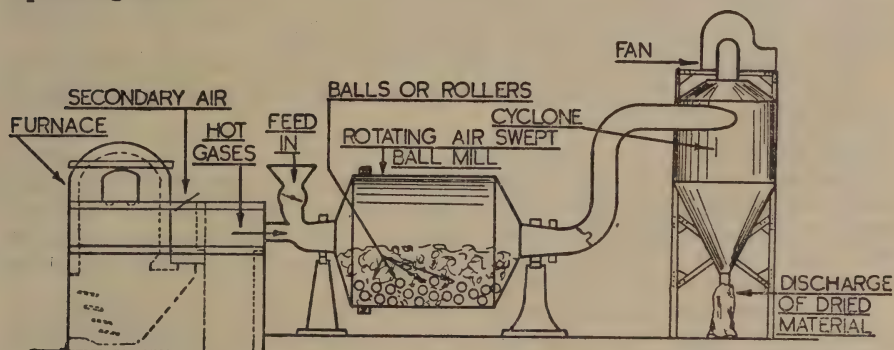


FIG. 23. Air-swept mill for pulverizing and drying.

VACUUM DRIERS

Driers of this type are expensive, as drying has to be carried out in vessels or chambers which have to be sufficiently strong to withstand external pressure, and a condenser and air pump are necessary to maintain the vacuum and draw off evaporated moisture. The majority of vacuum driers are batch driers, as a continuous feed drier necessitates the incorporation of a seal device to prevent loss of vacuum when the material enters and leaves the drier.

The great advantage of this type of drier is that the boiling-point of water is very much lowered, as shown by the following figures:

Vacuum—_inches of mercury ..	26	27	28	29
Boiling-point of water ..	125° F.	115° F.	101° F.	79° F.

VACUUM CHAMBER.

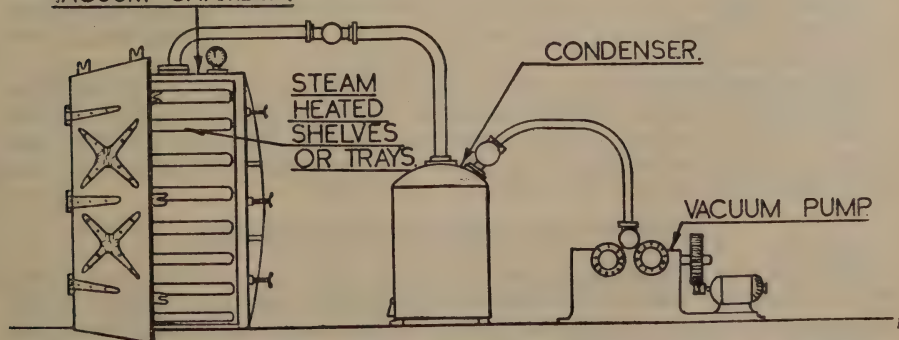


FIG. 24. Vacuum drier.

When drying in a vacuum, a high rate of evaporation can be maintained at a low temperature; consequently it is the best method of drying materials that would be harmed by drying at higher temperatures and are difficult to dry owing to the low rate of diffusion of moisture from the centre to the surface of the material. Sugar, chemicals, dyestuffs, rubber, white lead, foodstuffs, and explosives, are examples.

The material may be heated before it is put into the drier. Inside the drier the heating is by conduction through contact with the hot (steam-heated) metal surfaces of the drier, and to a lesser extent by radiation. It is sometimes necessary to provide revolving arms or agitators to turn the material over to equalise its temperature, or the material is spread in a thin layer on steam heated trays in the drier (Fig. 24).

The thermal efficiency of the vacuum drier is high, with a consumption of approximately 1.25 lb. of steam per lb. of water evaporated. Very economical working can be effected if exhaust steam is available.

Film driers are sometimes incorporated inside vacuum chambers to deal with material which can best be dried by this means and where there are added advantages in vacuum drying.

Freeze Drying

This technique, first developed over 50 years ago, has been applied on a large scale only within recent years. It has been evolved specially for drying heat-sensitive biological fluids (e.g. blood plasma, serum, penicillin, streptomycin, etc.) and certain foodstuffs. For the last-mentioned, its cost is still somewhat high for economic application.

The fluids are placed within the containers in which they may ultimately be stored or on trays, and submitted to a temperature of about 25°C. under vacuum (pressure: below 1 mm. mercury abs.). The water vapour condenses as ice (sublimes) on to the condenser coils, from which it may be scraped, or removed by other special technique.

The process is also used for the production of gels, e.g. silica gel, the latter being used as a desiccant. This method of vacuum drying offers some advantages over drying at higher temperatures. Among these are the preservation of the natural structure, promoted by the very rapid freezing, and the production in some cases of a porous structure facilitating making subsequent resolution (e.g. as in the case of blood plasma)^{6 7 8}.

SUNDRY TYPES OF DRIERS

There are various proprietary types of driers and others made for special purposes which do not come under any particular classification. One of these, for example, comprises an enclosed trough or casing inside which there is a reel of steam-heated steel tubes. Outside the tubes are paddle blades which pick up the material from the bottom of the trough and spill it into the nest of steel tubes as the paddles revolve.

Another special type is fitted with concentric ploughshare discs mounted in a casing which is about half filled with the material to be dried. The drying gases pass through the casing and heat the concentric discs, which revolve and plough through the material to be dried. The material is turned over by the ploughshares and heated by conduction from them.

RADIANT HEAT AND INFRA-RED DRIERS

All hot bodies radiate energy, some of which is within the heating or infra-red wavelengths. The terms infra-red and radiant heat are in this context synonymous. The application of infra-red radiation to industrial drying is a comparatively recent development, though it is really of ancient origin, an

example being the drying and airing of domestic laundry before the kitchen fire.

The wavelengths of infra-red radiations are generally expressed in microns, μ , or Ångström units, Å. Table 2 shows the relationship between infra-red radiations and other distinctive wave bands (see Appendix A).

A well-known use of infra-red radiation is the drying of paints and enamels on mass-produced articles such as motor car bodies, tin cans, etc. The field is now considerably wider and has been extended to such processes as the drying of photographic films and plates, chemicals, drugs, etc. Although infra-red rays may be produced by heating a surface by any means, in view of the ease of control only gas and electricity are generally used.

Electrical infra-red generators are normally of two types, lamps and bar generators. Both use a high resistance wire as the heat-generating element. In the lamp, the resistance is enclosed by a glass bulb. With bar generators the wire is wound on to a ceramic former. The wavelength and the intensity of heat emitted depend upon the generator temperature, which can be varied by adjusting the voltage applied. The lower the temperature of the generator the longer the wavelength. Hence lamp generators, which can run at higher temperatures, operate at much shorter wavelengths than do bar generators. On the other hand, it is impossible within a given space to obtain such high intensity of radiation from a lamp generator as from a bar generator.

Gas-heated generators give longer wavelengths, and higher intensity of radiation than do lamp generators. They are of two types

- (a) medium-temperature black emitters,
- (b) high-temperature incandescent emitters.

The medium temperature range in general has a source temperature of 450–650° F. and the high temperature range between 600–1,000° C. (1,100–1,800° F.). In the medium temperature range, radiation of wavelength about 5μ . or 50,000 Å at peak intensity is produced, the major part of the energy being radiated between 20,000 and 150,000 Å. The flux density or intensity of radiation in a typical gas heated oven using medium temperature panels is about 4,000 B.t.u. per sq. ft. per hour. In high temperature radiant tunnels the flux density can be of the order of 50,000 B.t.u. per sq. ft. per hour equivalent to about 100 watts per sq. in. High temperature sources working at about 1,600° F. emit radiation having a wave length at peak emission intensity of about 20,000 Å or about half that of a medium temperature panel. The gas heated black emitter panel consists of post-aerated ("neat") gas burners firing into a chamber insulated on one side and provided on the other side with a mild steel (or cast-iron) black panel.

There are various types of high temperature panels. Those using air blast or pre-mixed inputs include surface combustion units, in which a mixture of gas and air passes through a granular or perforated refractory material, combustion taking place on the surface. Other high temperature panels use *aerated* or *post-aerated** burners firing into a space bounded on one side by insulating refractory brick and on the other side by refractory radiants. Panels are available in a large range of sizes to suit requirements of the various processes.

The advantage of very short wavelength radiation is the high penetration of the waves, specially valuable for drying many types of paint, varnishes,

* *Aerated*: as in systems using the familiar Bunsen burner method of admitting air at the burner but immediately before the flame.

Post-aerated: as in the so-called luminous or batwing type of burner, all the air for combustion reaching the flame from the outside.

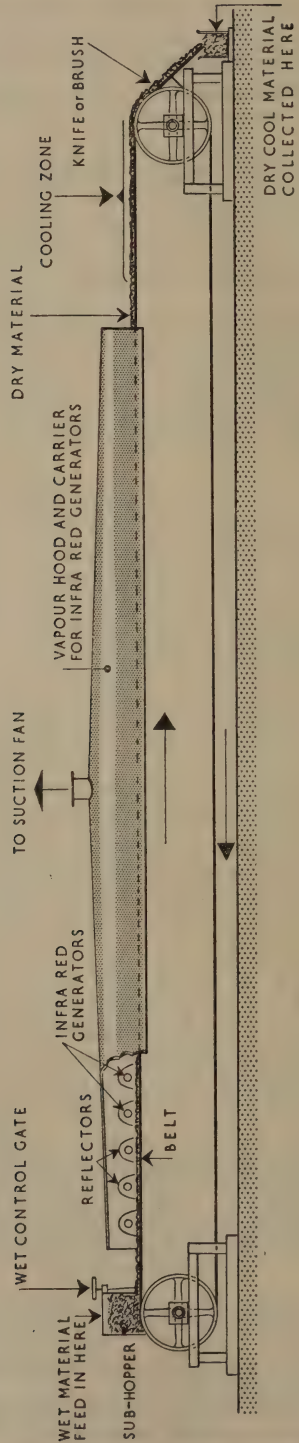


FIG. 25. Continuous infra-red drying installation.

lacquers, etc. Heat is "created" throughout the depth of the paint film, and drying takes place evenly without the formation of a hard protective skin before the inner layers are dry. In some applications the high penetration obtained is a disadvantage, for example, in drying transparent strip, cinematograph film, etc., where some of the rays pass right through the strip and thus do not generate heat within it. In such cases, long wave bar generators or gas generators are to be preferred.

Table 2 also gives the penetrative effects of infra-red radiation at varying wavelengths and the characteristic generator temperatures.

The application of infra-red methods to drying problems is not as simple a matter as it would appear at first sight; experts should always be consulted. Among other things, the choice of wavelength and the intensity of radiation are of particular importance and require careful consideration, not only on theoretical grounds but on the basis of empirical and experimental data. Pilot scale work in a laboratory is often necessary before embarking on the setting up of a large scale equipment.

Infra-red drying plants are generally of the continuous type, and some form of conveyor is used for carrying the articles through the infra-red radiation zone. For articles sprayed with paint, this is often a simple chain conveyor from which the painted parts are hung. For drying chemicals, however, different types of conveyor are necessary. One is of the vibrating deck type, generally used for drying free-flowing crystalline and powdered chemicals. The vibrations of the deck cause the material to progress in a forward direction, speed of travel depending on the frequency and amplitude of the vibration. The vibrations are applied either by an electro-magnet or a hydraulic piston mechanism. For drying sludge and sticky materials a continuous band conveyor is more commonly used, the material being picked up from a trough or feeder and, when dry, being brushed or scraped off at the other end. (See Fig. 25.)

The following are among the advantages of infra-red drying:

- (1) Drying is very rapid, often complete within seconds, as compared with the much longer period, running into hours or even days, generally necessary when using drying chambers.
- (2) The apparatus can be much smaller than the other types of driers for the same duty. In consequence, the capital cost is also frequently much lower.
- (3) The temperature can be kept down to a very low figure, even as low as 40–50° C., where there is risk of damage.
- (4) Control is usually simple and easy.
- (5) The plant can be started and stopped rapidly, without delay for lighting up and waiting for the heating chamber to attain the required temperature.
- (6) Thermal efficiency is generally high; comparing very favourably with that of other methods.

While it is not generally considered good practice to use high-grade energy for drying, the system can often be justified by taking into account the advantages enumerated above.

HIGH-FREQUENCY DRIERS

When a material is placed between metal plates to which a high frequency voltage is applied, heat is generated in the material as a result of the strong electrostatic field which is produced; the material acting as the dielectric of a capacitor.

A high-frequency voltage, of the order of 2–100 megacycles per sec., is produced by an electronic generator; the frequency depends upon many factors

TABLE 2
ELECTRO MAGNETIC RADIATION

Type of Ray	Wavelengths in Ångstrom Units	Penetration characteristics of Ray				Characteristic appearance Generator and approx. temperatures	Type of Generator
		Thro' quartz	Thro' glass	Thro' water	Thro' Opaque Solid bodies		
Gamma Rays ..	0.035- 1.0	V. Good	V. Good	V. Good	V. Good	—	—
" X "-Rays ..	1.0 - 2,000	V. Good	V. Good	V. Good	V. Good	—	—
Ultra-Violet ..	2,000- 4,000	V. Good	V. Good	V. Good	Poor	—	—
Visible Rays ..	4,000- 7,000	V. Good	V. Good	V. Good	Nil	White hot temperature above 2,000° C.	Electric lamps
Near Infra-Red ..	7,000- 20,000	V. Good	Good	Good	Nil	Very bright red hot, 1,500° C. and above	Electric lamps
Middle Infra-Red ..	20,000- 40,000	Moderate	Poor	Nil	Nil	Bright red 750° C.	Gas and electric bars
Far Infra-Red ..	40,000-100,000	Poor	Nil	Nil	Nil	Dull 500° C. and less to invisible	Gas, electric bars and Perolene Generators

such as the area of the material to be heated, the shape of the material and hence of the electrodes and the power required. Too high a frequency leads to unequal voltage distribution and local overheating. 15,000 volts is normal; higher voltages require additional precautions to avoid corona effects and arcing.

The chief feature of high frequency drying is the uniformity of heating and the fact that even a wet material can be heated at the centre as rapidly as at the surface.

This form of drying is used in the drying of artificial silk yarn, rayon cord, vegetables, sponge rubber, etc. and also in the removal of water from slurries and heat-sensitive solutions, as in the manufacture of penicillin.

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The reader is referred to the papers contributed to *A Study of Drying* during the 1950-51 session of the Institute of Fuel and to other numerous papers on the subject in the *Journal*.

CHAPTER 26

HEAT BALANCES OF FURNACES AND BOILERS

GENERAL PRINCIPLES

A HEAT BALANCE is a valuable guide to the efficient operation of industrial plant using fuel or power. Its primary object may be to determine the overall thermal efficiency of a boiler or other furnace; its greatest value lies in indicating the directions in which the heat supplied is utilized and, by comparison with known or previous standards, to detect whether any is being wasted and if so to what extent.

The performance of a heating unit may be expressed in terms of fuel used per unit of output. Thus the performance of a billet heating furnace can be assessed in pounds of coal per pound of billets heated, that of a boiler in pounds of coal per pound of steam raised, or that of a coke oven in cubic feet of gas burnt per ton of coal carbonized. This method is satisfactory so long as it is desired only to compare the performance of plant doing exactly the same work, but it cannot effect more general comparisons. The relative performance of two cement kilns, for example, is not in any way assessed by the statement that one uses 30 lb. of coal A to burn 100 lb. of clinker from a slurry containing 43 per cent. moisture and the other uses 20 lb. of coal B to burn 100 lb. of clinker from a slurry containing 33 per cent. moisture. In such cases it is first of all necessary to express the data in terms having a common basis. A suitable basis is the quantity of fuel required to treat or produce unit quantity of material, under ideal conditions.

Performance may then be determined in terms of the ratio of the weight of fuel ideally necessary to the weight of the same fuel required in practice. This computation is based on the law of conservation of energy, which implies that although the various forms of energy in a given system may be mutually convertible, the total quantity of energy remains constant, there being no total gain or loss in the process.

When a combustible of constant composition, e.g. carbon, is completely burnt (C to CO_2) a fixed and definite amount of heat is generated in the process. When 1 kWh of electricity is absorbed in a resistance, 3,413 B.t.u. are liberated.

When several processes are carried on simultaneously, if all the energies in the reacting materials before the process are expressed in one set of units—e.g. B.t.u., or ft.-lb.—they precisely equal the sum of the energies after the processes, expressed in the same units. For example, if electricity is used to lift weights, the total energy of the electricity used is exactly equal to the sum of the energy absorbed by lifting the weights and of that appearing in the form of heat in the bearings of the machinery used.

It follows from this law, that any given process requires a certain and definable minimum of energy. To heat 100 lb. of steel billets from $25^\circ C.$ ($77^\circ F.$) to $1,100^\circ C.$ ($2,012^\circ F.$) requires approximately 31,500 B.t.u. This figure is given by the expression

$$\text{weight} \times \text{specific heat} \times \text{temperature rise.}$$

No furnace heating these billets through this range of temperature could use less than that amount of heat. This means that the fuel consumption cannot be less than 2.5 lb. of coal having a C.V. of 12,500 B.t.u. per lb., which we may take as our standard coal for the purpose of the discussion. ($31,500 \div 12,500 = 2.5$). Similarly, the production of 100 lb. of saturated steam

at 250° F. (121° C.) and 30 lb./sq. in. abs. pressure, from water at 60° F. (16° C.) requires 113,700 B.t.u., for which 9 lb. of the "standard coal" would be required.

If liquid fuels are being considered we could take as our standard an oil fuel with a net C.V. of 17,670 B.t.u./lb. On this basis the production of 100 lb. of steam would require 6.43 lb. of oil fuel.

A word of warning must here be uttered regarding the use of the expression *standard*. It is used here, and elsewhere in this chapter, merely as a convenience to have a basis for developing the argument. There is no intention to imply that any of the figures chosen have, in fact, been accorded the sanction of official usage.

This method of assessment of appliances on a purely thermal basis is of much greater value than the simple statement of pounds of fuel per 100 lb. of product. The relative performances of appliances may then be compared after evaluation in this manner.

Useful as this method of assessment is, it is only a measure of overall performance—an index of the plant efficiency. Although it may show that performance is bad, it provides no clue to the cause. This can only be elucidated by a more detailed application of the principle of conservation of energy. The principle is best applied in the form of a *Heat Balance*, which is nothing more than an attempt to balance the total energy entering a system against that leaving, following the pattern of a financial balance sheet. In both the input and the outgoing sides of the balance, all the forms of energy involved must be considered. Their magnitudes must, of course, be expressed in the same heat units, and with reference to a suitable common datum temperature, usually either 32° or 60° F., alternatively 0° or 15° C. Such heat balances may refer to a period of time, such as one hour or the time required to complete a given cycle of operations, or they may be based on unit quantity of material treated or manufactured. Typical items to be found in such a balance are as follows:

Input:

- (1) Chemical energy of fuel, sensible heat of fuel (if above the datum temperature), and of the air supplied for combustion. Sensible heat (above datum temperature) of the material heated. Electrical or mechanical energy supplied to such auxiliaries as fans or pumps.
- (2) Heat evolved in exothermic reactions.

Output:

- (3) Total heat content of the outgoing material heated. This may include sensible, and latent heat.
- (4) Heat absorbed in endothermic reactions. (See Chapter 7.)
- (5) Total heat of the exit combustion products. This usually consists largely of sensible heat, and of the latent heat of steam in the exit gases, but any undeveloped heat due, for example, to the presence of other unburnt gases, e.g. CO, must also be included.
- (6) Heat losses from the structure, due to conduction through the walls and crown with subsequent radiation and convection from the external surfaces. (Methods for assessing heat loss by conduction into the ground are given in more advanced treatises.)
- (7) Miscellaneous and special losses. These may include such items as cinder loss in solid-fuel-fired appliances, cooling water losses, heat radiated through open doors or sightholes, conduction losses through a long charge projecting from a furnace, losses in bogies and certain conveyor-type furnaces in which the mechanism employed has an opportunity to cool outside the heating chamber.

In assessing thermal balances care must be taken to ensure that they are not invalidated by ignoring heat stored in the structure, or received by it. It is, therefore, important (i) that the furnace should be in the same thermal condition at the beginning and the end of the test or (ii) that the test shall be conducted over a long enough period to cause heat evolved or absorbed in this way to be negligible, or (iii) that due allowance be made for the sensible heat stored in or evolved from the structure.

It is frequently not possible or economically worth while to determine every item exactly. Undetermined items should be shown as "unaccounted losses", being the difference between the heat input and the sum of the measured items on the output side. The relative magnitudes of the unaccounted losses can serve as a guide to the accuracy of the heat balance as a whole.

Item (1) is always of major importance and items (2), (3), (4) and (5) are almost always equally so.

The magnitudes of items (6) and (7) depend on the nature of the plant concerned. It is advantageous, wherever practicable, to make additional check measurements. For example, conduction losses through the structure walls may be calculated from a knowledge of the temperatures concerned and the thermal conductivity and dimensions of the walls. It may be useful to compare the figure so obtained with one determined on the basis of external surface temperatures and such radiation and convection data as those given by Spiers.¹

Further discussions on heat losses will be found in Chapters 19 and 20.

THE CONSTRUCTION OF HEAT BALANCES

The first step is to determine how detailed the heat balance should be. An overall balance, comprising nothing more than the calculation of the total energy entering and leaving the system is relatively simple, but gives no information of the relative effectiveness of the different parts of the system, the fuel bed, the heating chamber, the recuperator, and so forth. At the other extreme it may be possible to subdivide a furnace into a large number of zones and make a complete heat balance for each. This will require many more measurements, but when it is possible to make the measurements it will give much more detailed information. Practical conditions generally prevent this from being done.

To determine the sectional heat balances is one of the most difficult operations facing the combustion engineer, because of the complicated nature of the calculations relating to radiation losses. It is, therefore, usually best to make a compromise and divide the system into several main parts, and make a heat balance for each of these units. Thus, a boiler plant may be divided into boiler, superheater, economiser and air heater, if the gas and steam or water measurements are made at the entry and exit of these parts. Similarly, an open hearth furnace can be divided into producer, mains, regenerators, and working chamber.

The second step is to obtain the necessary measurements. The chemical energy of the fuel is measured in terms of quantity used multiplied by its calorific value in the same system of units, and is commonly expressed in therms. Producer gas made from coal contains tar which adds materially to the calorific value of the gas. If part of this tar is condensed in the mains the loss must be debited to the process if the C.V. taken is that of the crude gas leaving the producer (i.e. still containing the tar).

The sensible heat absorbed by the charge may, as indicated on page 692, be calculated from the temperature range involved and the specific heat and weight of material treated. In cases where large masses such as ingots are

heated,¹ the possibility that the material may not be fully soaked should be borne in mind. If a large temperature differential is likely it might be possible to calculate the average temperature by the techniques discussed in Chapter 20, or by reference to a more advanced treatise on heat conduction such as that due to Carslaw and Jaeger.²

The determination of the thermal effects, both endothermic and exothermic, that may occur in the heating of the charge, may be even more complicated. In the heating of metals, for example, thermal properties vary with temperature; with steel, in particular, there may be a change of state occurring between 700° and 750° C. associated with an absorption of heat during heating, giving a latent heat of change of state. This involves only a physical change. Where chemical reactions between substances are also involved there enters the question of heat of reaction, which may vary with temperature, and even at a specific temperature become negative with the reaction reversed in direction. By way of illustration, a summation of the thermal effects is given below for acid and basic open hearth melting. Endothermic effects involve heat absorbed in forming slag, decomposing limestone and reducing the oxides of iron. Exothermic effects arise from oxidation of metals and metal-loids and in slag formation. The values shown are percentages of the total heat involved in the bath.

		<i>Heat absorbed (endothermic)</i>	<i>Heat evolved (exothermic)</i>	<i>Heat from chemical reactions available for melting</i>
Acid	..	8.8	58.5	49.7
Basic	..	18.5	46.0	27.5

The consumption of fuel has to provide the balance of heat required. Data on thermal effects of established processes can be obtained by reference to the special textbooks on the subject.

The calculation of the heat contents of exit gases can be calculated according to the principles discussed in Chapter 7.

The quantity of these gases may be also obtained by calculation as there described. If, however, hot, crude producer gas is used, it may be possible to measure only the weight of fuel gasified in the producer. The quantity of producer gas can then be deduced from the amount of carbon consumed in the producer (i.e. carbon charged less carbon in ashes and dust and tar deposited in the mains) and the amount of carbon in 1 cubic foot of the gas as fed to the furnace.

For British producer coals, a reasonable allowance of 7 per cent. of the carbon in the fuel can be made for the tar formed in gasification, though the precise figure will depend upon the design of the plant.

Useful information is provided by the calculation of materials balances, derived from the compositions of the fuel and the gas. Thus the Carbon Balance enables the volume of gas per pound of fuel gasified to be computed. The Hydrogen Balance on the input and output of the producer makes it possible to calculate the amount of steam decomposed in the producer. The Oxygen Balance provides a check on these two calculations.

A feature of uncertainty in assessing the performance of a producer is the influence of the wetness of the blast, much of the condensed steam being filtered out in the ash bed. This involves an aspect of producer operation requiring further research.

The heat losses to the surroundings often prove to be the most difficult item to assess accurately. It is often included with the unaccounted losses, being

thereby obtained by difference. However, it is preferable to make a direct and separate estimate of as many of these losses as is practicable.

The heat used up in water-cooling can be readily calculated from measurements of the quantity of water passing and its temperature rise, provided precautions are taken to obtain the true mean temperature of the water. This measurement is always well worth making, even where the other heat losses cannot be measured, in order to see whether the system is excessively cooled.

Such results may be very approximate because the so-called "steady conditions" of thermal equilibrium are rarely reached in practice, particularly in plants in which there are periodic variations in temperature.

GRAPHICAL HEAT BALANCES

THE SANKEY DIAGRAM

For the purpose of considering how a full heat balance can be represented diagrammatically it should be assumed that it is possible to make a complete heat balance for all stages of a process. The heating medium arrives at each stage with a known content of chemical and sensible energies, and leaves with other known values. A known amount of heat is given to the material being heated, and a known amount to the furnace structure. The results can then be expressed graphically by means of a heat flow diagram, also termed a "Sankey diagram". An outline diagram is made of the system, showing the various parts and their interconnection. The flow of energy is then represented in this diagram as a stream flowing through the system. Convenient units in which to express the energy are therms, or pounds of a standard coal, or cubic feet of a gas, or gallons of a standard fuel oil per 100 lb. of product. This method has the advantage over the use of percentages that if two diagrams are made for different furnaces producing the same material, the relative fuel consumptions are shown directly. Since the difference between the two methods is purely numerical and leaves the diagram identical, they can both be used by adding appropriate scales.

Some examples of heat flow diagrams for various industrial processes are given in Figs. 2-7.

As an illustration of the construction of a simple Sankey diagram, we can take the case of an oil-fired Economic boiler generating 6,000 lb./hr. of steam at 150 lb./sq. in. g., from feed water at 100° F. The heat balance expressed in B.t.u./hr. is as here tabulated. (It is emphasized that the figures given are merely illustrative and not intended to be regarded as typical or average.)

<i>Input</i>	<i>B.t.u.</i>	<i>Output</i>	<i>B.t.u.</i>
Feed water at 100° F. . .	240,000	Steam	7,005,000
Oil: 466 lb./hr.	8,200,000	Flue loss	1,275,000
		All other losses	160,000
	<u>8,440,000</u>		<u>8,440,000</u>

The balance shows an efficiency, on the net C.V. basis, of 82.5 per cent.

Alternatively, the basis for measurement may be taken as the number of pounds of oil used per 100 lb. of steam generated. If the net C.V. of the oil is 17,600 B.t.u./lb. the figures in the above statement would then be divided by the product $17,600 \times 6,000$, i.e. $17,600 \times 60$, thus:—

<i>Input</i>		<i>Output</i>	
Feed water	0.23	Steam	6.63
Oil	7.77	Flue loss	1.21
		All other losses	0.16
	<u>8.00</u>		<u>8.00</u>

Fig. 1 shows in diagrammatic form the ingoing and outgoing heat in the form of a wide ribbon, the widths of the different portions of which are proportional to the amounts of heat represented.

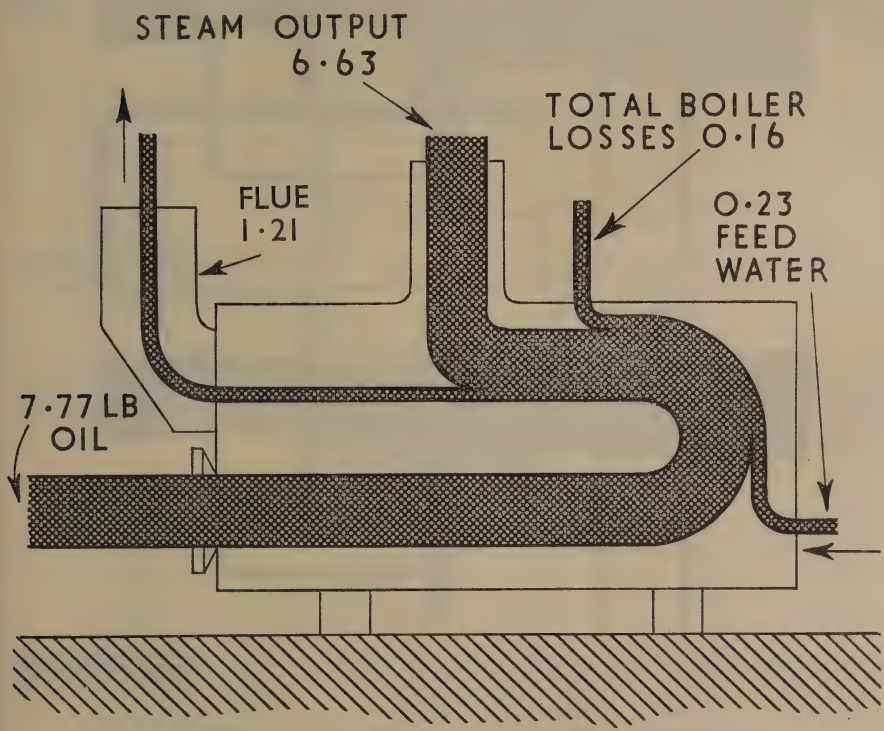


FIG. 1. Simple diagrammatic heat flow diagram or Sankey diagram.

The boiler represented in Fig. 2 is an industrial water-tube boiler, burning coal and incorporating an economiser and superheater. Heat transfer may be divided into three stages, i.e. to the boiler tubes, to the superheater tubes and to the economiser tubes. The figures are calculated from separate actual tests carried out on one and the same boiler plant, the example marked "poor" representing the conditions on the plant "as found". By regulating the draught and controlling the air distribution to the fuel beds and by ensuring that the fuel completely covered the grates the efficiency was improved. The example marked "good" represents the working conditions on the plant after the stokers had completed a course of instructions on boiler firing. Thus the boiler efficiency was increased from 64.7 per cent. to 78.5 per cent. merely by improving the combustion conditions.

Fig. 3 represents a modern power station boiler and demonstrates that higher efficiency (in this case 84.5 per cent., as compared with 65.5 per cent.) depends on the installation of an economiser and an air heater. The figures are calculated from published data.

The continuous vertical retort, Fig. 4, represents one phase of modern gasworks practice in which the coke leaving the retort gives up much of its heat to the secondary combustion air, the sensible heat in the gas leaving the top of the retort is partly utilised to preheat the incoming coal, and the flue gases are passed in counterflow to the incoming coal and are subsequently passed through a waste heat boiler. The figures are calculated from published

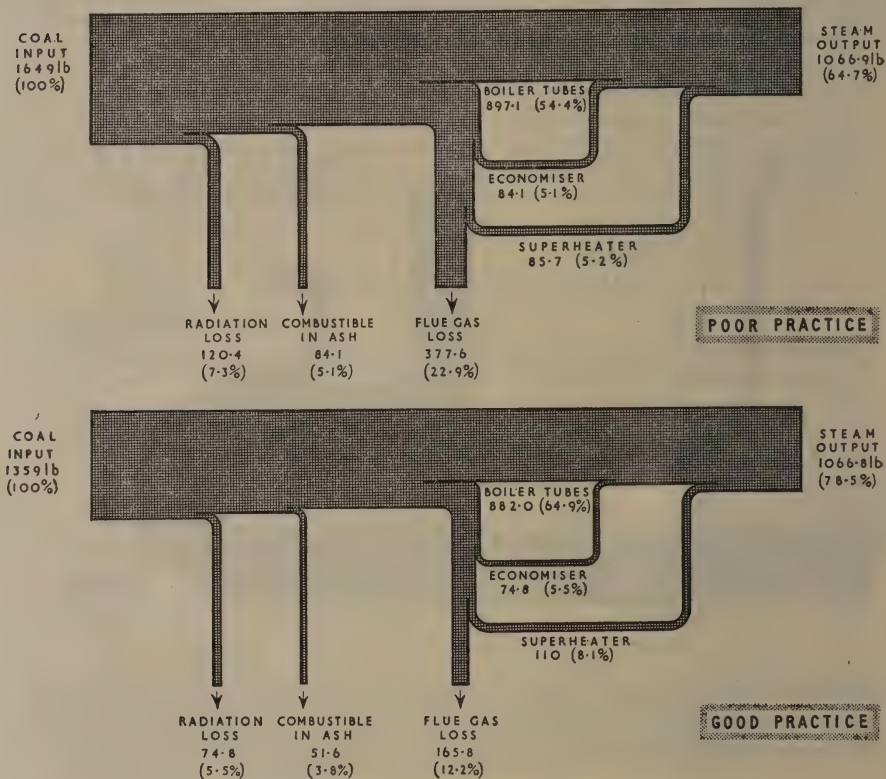
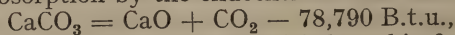


FIG. 2. Heat flow diagram for an industrial water-tube boiler.

data³. The chief difference between high and low thermal efficiency arises from the absence of a coke cooler and a waste heat boiler. If these principles could be carried to their logical conclusion, all the heat supplied to the retort would be available for steam raising, as most coals require a negligible amount of heat for endothermic reactions in carbonising.

Cement kilns, Fig. 5, represent another example of counterflow heating, with the difference that heat transfer is here much simpler because the gases can be mixed with the material being heated. In this process there is an appreciable heat absorption by the endothermic reaction:



so that the heat supply cannot be reduced below this figure, but, as in the gas retort, the sensible heat of the *fired* clinker can be returned in the form of pre-heat of combustion air. A cement kiln working with a wet feed (slurry) has also, of course, to evaporate a large quantity of moisture; the sensible heat of the water vapour produced is not recoverable. This however does not represent an ultimate limitation of the process. The improvement represented is due mainly to improved combustion and better insulation.

In the regenerative glass tank (Fig. 6)⁴ the gases leave the furnace at a very high temperature and the attempt is made to re-cycle as much of their heat as possible by regenerators. The heat lost in the furnace and regenerators is of the same order of magnitude as that utilized; consequently the difference between good and bad practice lies mainly in extent of the heat losses.

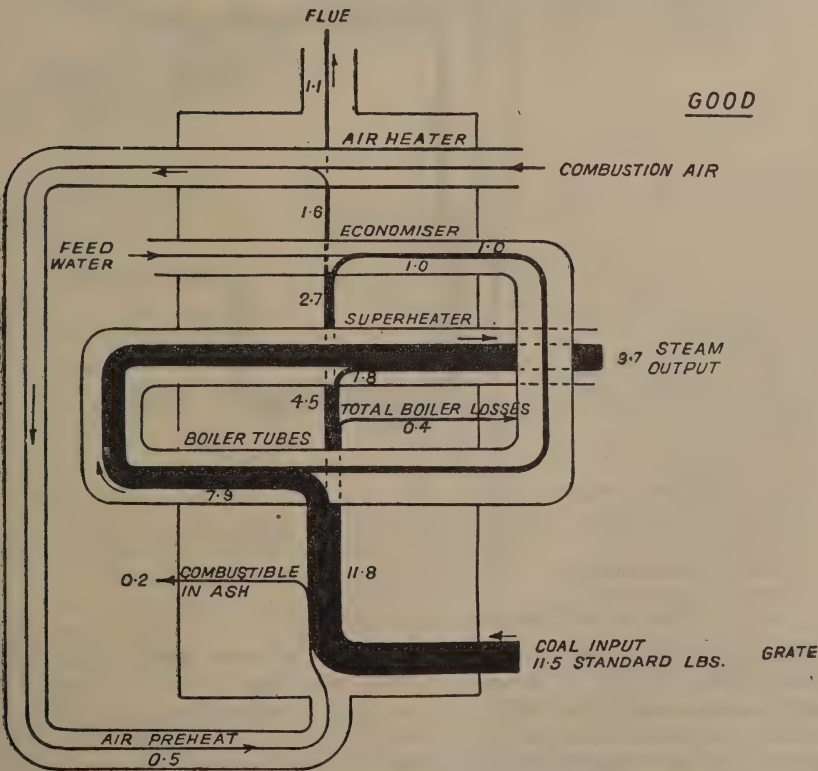
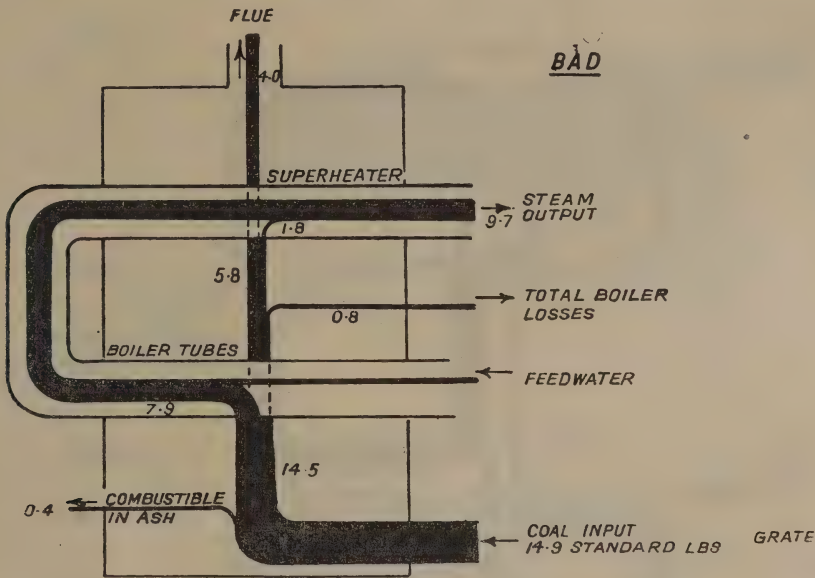
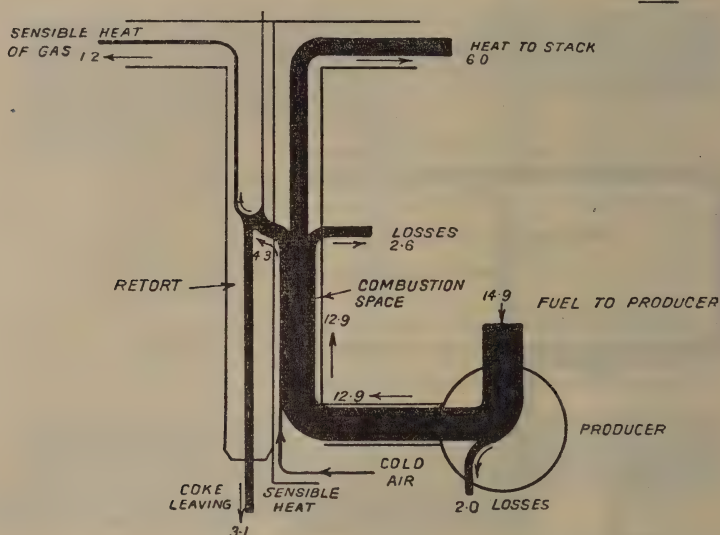


FIG. 3. Heat flow diagram for a large water-tube boiler

BADGOOD

ALL FIGURES REFER TO LBS
OF STANDARD COAL PER 100
LBS. OF COAL CARBONISED

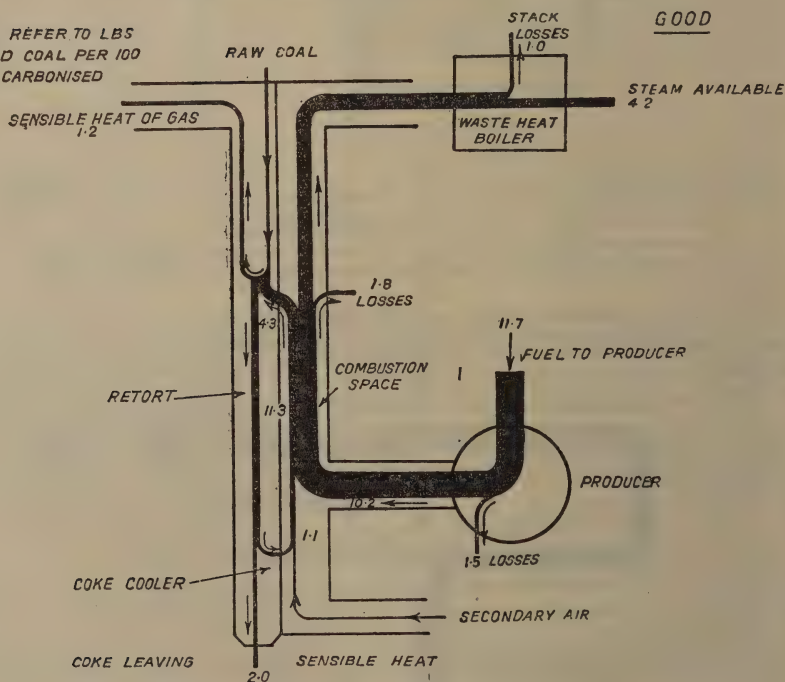


FIG. 4. Heat flow diagram for continuous vertical retort.

Precisely similar considerations⁵ apply to the open hearth steel melting furnace shown in Fig. 7. In studying the diagrams given for "Good" and "Bad" performance, it is important to keep in mind that it is difficult to compare the performances of Open Hearth furnaces, where the metallurgical considerations are the over-riding factor. In both the glass tank and the open hearth furnace it is often desirable to install waste heat boilers because,

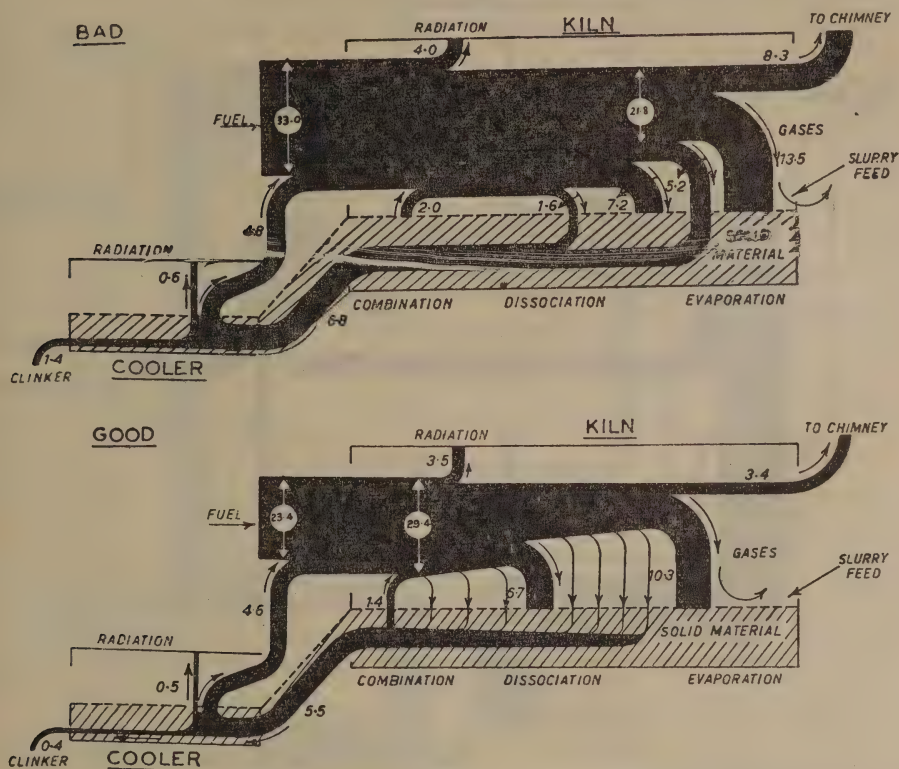


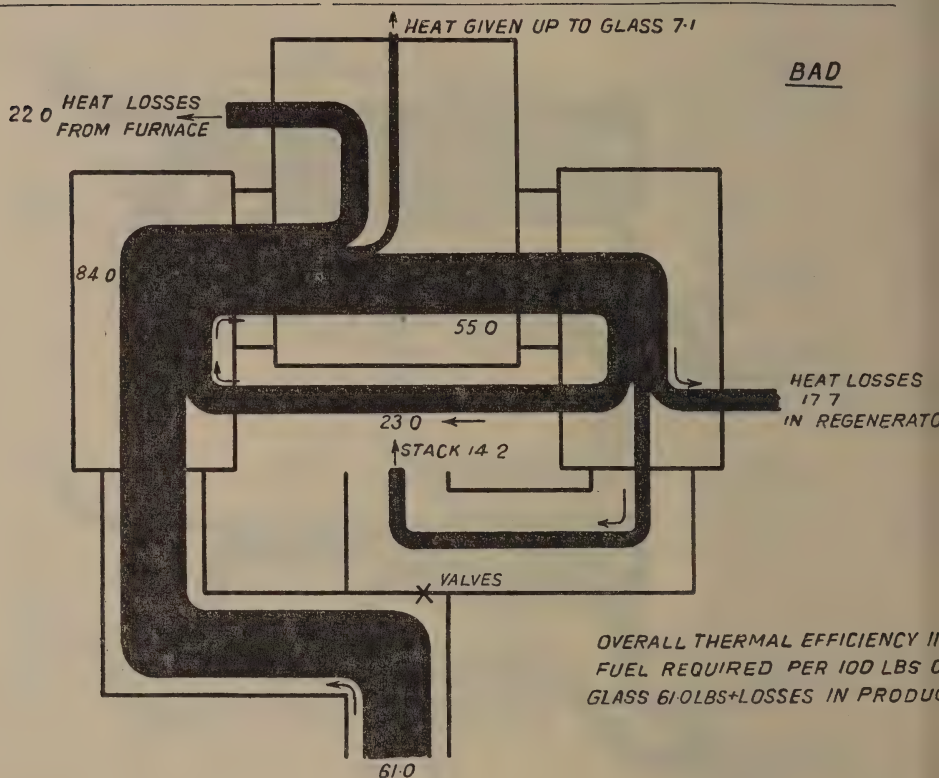
FIG. 5. Heat flow diagram for cement kiln.

owing to limitations in regenerator size and rates of heat transfer, the regenerators do not cool the gases below 700°–800° C.

THE HEAT REQUIREMENTS OF DIFFERENT SYSTEMS

The heat flow diagram shows whether a system is operating effectively, in terms of heating efficiency, i.e. in relation to the quantity of energy supplied and utilised. It does not, however, show directly the effect of the quality of the energy concerned, but this effect can be derived indirectly from it. Energy is in itself of no value unless it is also of sufficiently high quality to perform the work for which it is required. The Sahara Desert, for example, contains an enormous quantity of heat but it is of no practical value (at present) for the generation of power. It could be effectively used only if some very large colder body, of great heat capacity, were placed alongside it. Similarly, combustion gases at a temperature of about 800° C. are useless for melting steel, but their energy is of sufficient quality to be valuable for raising steam.

A convenient way of assessing the quality of a given source of energy for a given purpose is to calculate the fraction of the energy ideally available. If combustion gases (assumed to be of constant specific heat) at a temperature T_1 are required to heat material to a temperature T_2 , one fraction of the energy, A, of magnitude $\frac{T_1 - T_2}{T_1}$, is available for the purpose and the remaining fraction, B, of magnitude $\frac{T_2}{T_1}$ is not. Temperatures, it should be noted, are on



REGENERATIVE SYSTEM FIRED WITH
PRODUCER GAS. ALL FIGURES REFER
TO LBS OF STANDARD COAL PER
100 LBS OF GLASS

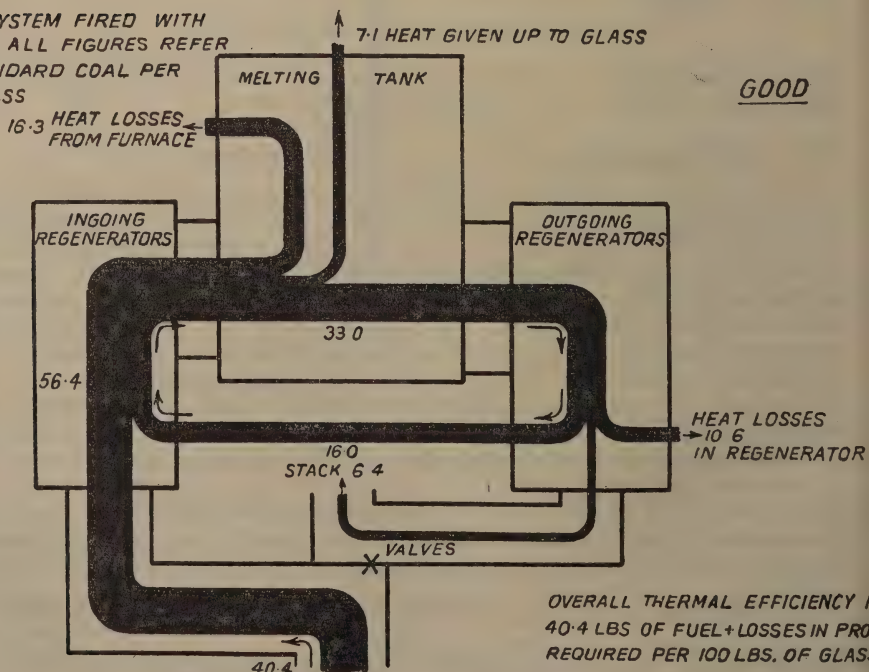


FIG. 6. Heat flow diagram for glass tank.

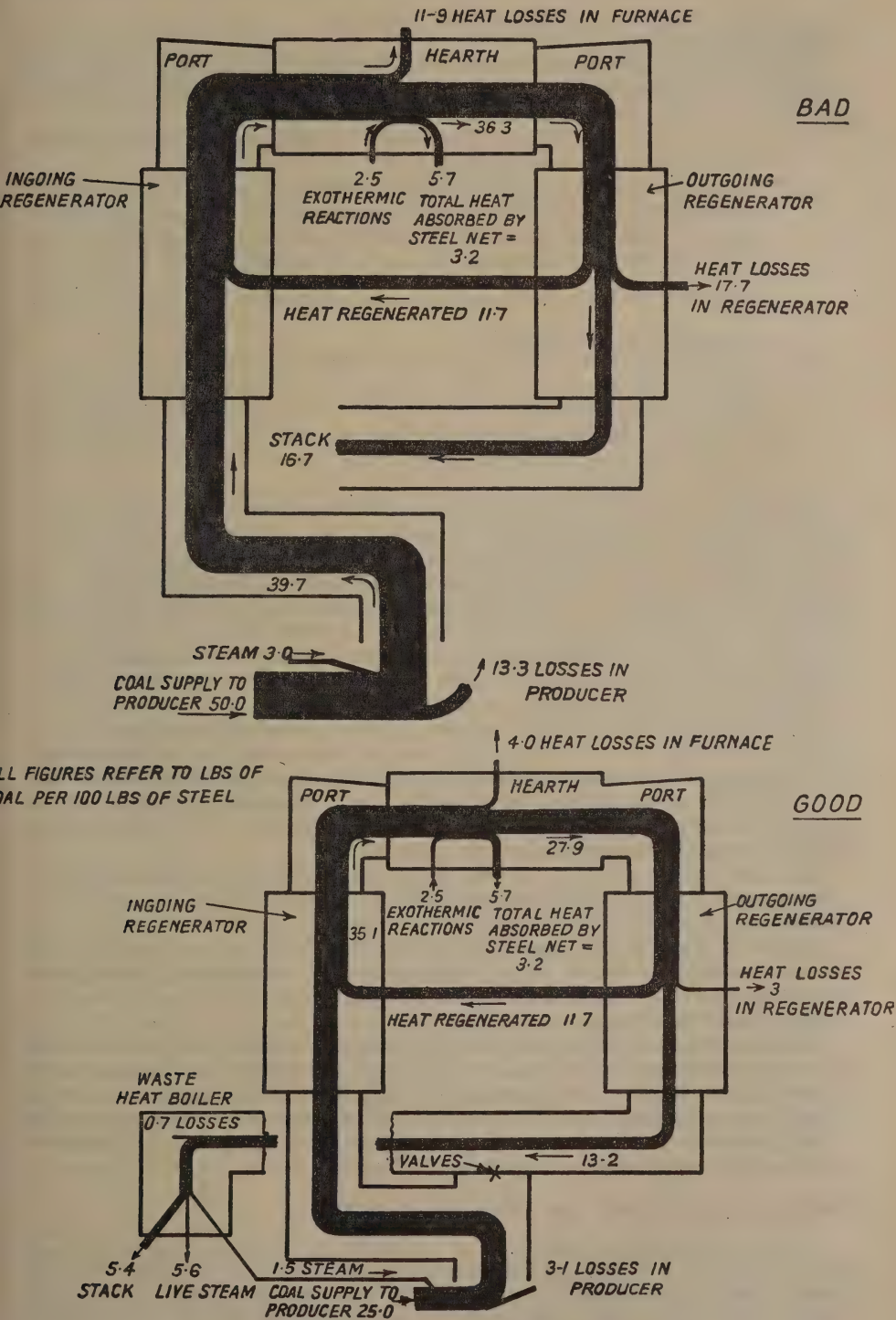


FIG. 7. Heat flow diagram for open hearth steel furnace.

the Absolute (metric) or the Rankine Scale, i.e. $t^{\circ}\text{C.} + 273 = T^{\circ}\text{A.}$, $t^{\circ}\text{F.} + 460 = T^{\circ}\text{Rankine.}$

The heat flow diagram can be used to investigate for various processes the conditions governing the best use of these two fractions. The conditions governing the best use of fraction A are as follows:

- (1) The fraction A should be made as large as possible by obtaining complete combustion with a minimum of excess air.
- (2) The heat transfer in the primary region should be as complete as possible so that the gases are cooled as nearly as is possible to T_2 in this region. How well these conditions are fulfilled is shown in the diagram by comparing the ratio of the heat leaving the primary region to the heat retained in it, with the ideal ratio : $\frac{T - T_2}{T_1}$ where T_1 is the theoretical temperature of combustion.
- (3) The heat retained in the furnace must be put to useful purpose by avoiding heat leakages; i.e. by the use of insulation (where possible), reduction of radiation through openings and of other unnecessary heat losses as described in Chapter 19. The success with which this is done is shown in the diagram by the ratio of the heat lost to the heat usefully applied in the furnace.

Fraction B cannot be used for heating at the maximum temperature of the process, but the diagrams show three satisfactory applications for it. In the steel and glass furnaces it is used to pre-heat the ingoing air and fuel gas, and in the boiler to pre-heat both feed water and combustion air and in the gas retort to pre-heat the air, thus raising the theoretical temperature of combustion, and increasing the value of fraction A. Here, just as in the furnace itself, the conditions whereby the best use may be made of the regenerator, recuperator, economiser or air heater are adequate heat absorbing surface, good insulation and minimum air infiltration.

The second method of using fraction B is the counterflow system typified by the vertical gas retort, cement kiln, and to some extent by the boiler. Here the material to be heated requires heat below the maximum temperature and this amount is of the same order of magnitude as the amount required at the maximum temperature. The low-grade heat can therefore be partly used for the first stages of the heating of the material.

The last method of using fraction B is for lower-grade purposes relatively unconnected with the main process. This is exemplified by the waste heat boilers on the steel melting furnace or gas retort.

Furnaces using any of these methods for the utilization of fraction B are thermodynamically sound, since they use heat of successively lower grade for work of correspondingly lower grade; they are an industrial approximation to the ideal reversible process.

In this way a study of the heat flow diagrams can be made to reveal indirectly the success with which the quality of energy is being utilized just as it also reveals similar information regarding the utilization of the quantity of energy. It will repay the time spent to construct such a diagram for any appliance in which energy is of major importance, to indicate promising lines for improvement as well as to show outstanding deficiencies.

INFLUENCE OF LOAD ON THERMAL EFFICIENCY

A vital consideration which must be borne in mind in interpreting any heat balance is the relation between the useful heat and the load. A heat balance only characterizes the performance of the plant at the particular load used in the trial. A better performance may always be obtained if the plant

is operated at its optimum load. At the optimum load (A Fig. 8) for a given set of operative and technical conditions, a maximum value of thermal efficiency is obtained. The general relationship follows a curve of the type shown in Fig. 8.

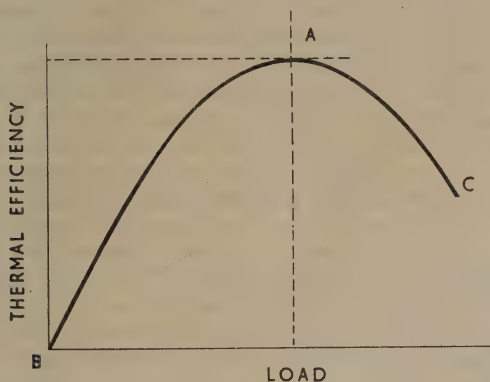


FIG. 8. Influence of load on furnace efficiency.

The efficiency of a boiler falls if it is overloaded because it is then operating on the section AC. Most furnaces (for example metallurgical and rolling mill furnaces) are worked on the BA Section of the curve and thus improve in efficiency as the load is increased. Neglect of this simple fundamental relationship is probably the main cause of inefficient operation where the output of plant is subject to variations of imposed load, a point all too often unheeded because of market considerations. The ideal in design is to obtain an efficiency/load curve with a wide flat apex, not so readily obtainable for high temperature operations when the considerations discussed in this chapter have been taken into account.

If a furnace heating several articles is filled to capacity (i.e. "fully loaded") less heat is required for each unit of material heated than when the furnace is operated to heat fewer articles at a time, since the flue gas loss, radiation and convection losses, etc., are just as high—sometimes higher—when heating a small load as when heating a large load.

The "thermal efficiency" of a furnace in which material is held for a period will be lower than that of a furnace in which it is necessary only to heat the same material to the same temperature and discharge it from the furnace immediately the temperature is attained.

It will be appreciated from the foregoing that, owing to the varied nature and complexity of furnace operations, the precise technique of determining heat balances and efficiencies must be governed largely by individual considerations applicable to each particular case. In the case of steam boiler plant, however, it is possible to prescribe a much more rigorous code of procedure as a guide. In view of this fact, and since the use of comparatively small steam-raising units is so widespread in industry, the remainder of this chapter is devoted to boiler testing, the procedure being moreover a good example of the manner in which a test may be conducted.

BOILER EFFICIENCY TESTING

The procedure in boiler testing will depend upon the extent of the information that is required and also upon the size and skill of the staff available for the work and the extent to which they are provided with instruments. There may well be a difference in procedure between routine testing undertaken to

keep the plant in good order and a more comprehensive test undertaken at much longer intervals to ascertain a complete heat balance. The simple procedure prescribed in 1939 in B.S. 845⁶ may still be accepted as a useful guide for testing most boiler installations. Its object is to indicate the methods which should be adopted and data that are necessary when carrying out a simple efficiency test, at minimum cost, on steam-raising plants using solid fuel. A warning must be given to the effect that if a true working efficiency is required or if the load on the boiler fluctuates, the period over which the test is run must be sufficient to embrace a complete cycle of such fluctuations. Thus a test period of one day or one week may be necessary. As issued in 1939, B.S. 845 was not intended for use in comprehensive tests such as are needed for large boilers. At the time of going to press it is being revised, partly on the basis of the code drawn up many years ago by the Inst. of Civil Engineers and in consultation with the Inst. of Mechanical Engineers. In the revised form it will provide the engineer and consultant with a valuable tool suiting the needs of tests for the large boiler installations.

B.S. 845 prescribes the minimum number of readings to be taken and the calculations required. As will be seen from the test results given later in this chapter, this method determines the overall thermal efficiency, and the losses in flue gases and ashes. All other losses are taken as a difference figure. The results, moreover, are referred to the net C.V. of the fuel. The original Inst. C.E. code was based on gross C.V.

The net C.V. is sometimes termed the "available" C.V. since it does not credit the latent heat of condensation of water present in the products of combustion (including water originally present in liquid form), heat that is not, in practice, available for raising steam or for heating material in a metallurgical furnace.

The difference between gross and net C.Vs. depends upon the percentage of combined hydrogen in the fuel as well as on the moisture content. The former varies considerably in solid fuels, from 0 per cent. up to over 5 per cent. For most coals it is convenient to take the difference between gross and net C.V. as being 3.5-4 per cent. of the gross C.V. As most liquid fuels contain 11-12 per cent. of hydrogen, the difference is of the order of 1,100 B.t.u./lb., i.e. about 6 per cent. of the gross C.V.

As a result, the thermal efficiency figure obtained by using the gross C.V. will in the case of most coals be about 3 per cent. (or less) lower than that by using the net C.V. and in the case of oil fuels, about 5 per cent. less.

These differences, 3 per cent. and 5 per cent. respectively, relate to relatively high efficiencies on which the influence of the difference between net and gross C.V. is greater than it would be on low efficiency figures.

Either gross or net C.V. can be used as the basis for the calculations, and conflicting views are held as to which should be preferred. Many industrialists in Britain favour the use of the gross C.V.; others prefer the net C.V. Whichever value for C.V. is used the possibility of conflicting results being arrived at must be kept in mind. The Institution of Civil Engineers Code is based on the gross C.V. On the Continent, the lower (i.e. net) C.V. is normally used; consequently it is prudent to remember that a boiler efficiency quoted abroad as (say) 85 per cent. will, if the net C.V. is used for the calculation be the equivalent of about 82 per cent. or 80 per cent. in normal British practice for coal-firing or oil-firing respectively. The position in the U.S.A. appears to be similar to that in Britain, both systems being adopted.

Specialist knowledge is required to ensure that reliable results are obtained by testing. Such knowledge can be acquired only by practice, but practice is often difficult to obtain, and therefore it is advisable to secure assistance for

at least the first test from an engineer who has had practical experience in boiler testing, and who will advise as to details of methods, instruments and how to avoid inaccuracies of measurement.*

Before making a test to establish a standard of performance, the boiler and its auxiliaries must be in such condition that all avoidable losses are eliminated. This means that all heating surfaces, both internal and external, must be clean; that no leaks of water or steam occur; that no air leaks occur through the setting of the boiler or the flues; that the grate is in good condition, and that the air supply is effective.

The fuel used for a performance test should be representative of that which will normally be used.

The thermal efficiency of a boiler may be determined in two ways by:

- (a) Direct measurement, and
- (b) Indirect measurement.

The direct method necessitates the measurement of the heat supplied by the fuel burned and of the heat usefully transmitted. While this method is recommended it is recognised that in some works it may not be convenient to make suitable arrangements to determine the weight of fuel and water. In such cases it is necessary to make use of the indirect method, which consists of ascertaining the various losses, and after expressing these as percentages, deducting their sum from 100; the resultant then gives thermal efficiency of the boiler plant.

BOILER TEST MEASUREMENTS

If the best results are to be got from a boiler, certain quantities and qualities must be under constant observation. This can be done easily if the boiler is properly equipped with suitable and reliable instruments maintained in good working order. The ideal is so to equip the boiler that it can be always operated under test conditions.

Even the smallest plant should be provided with enough instruments to let the operators know what is happening. The minimum equipment is that which will give the following information :

- (1) Measurement of coal burnt over given periods.
- (2) Output of boiler plant in lb. of steam or weight of water evaporated.
- (3) Temperature and pressure of steam.
- (4) Temperature of flue gases.
- (5) Temperature of water entering economiser.
- (6) Temperature of water leaving economiser.
- (7) Draught at base of chimney.
- (8) Draught at economiser inlet.
- (9) Draught in furnace.
- (10) CO_2 content of flue gases.

With larger plants, equipment on a more generous scale is a wise investment; if properly used it will pay for itself many times over.

TEST PROCEDURE

In what follows it is assumed that the object of the test is to ascertain what is the best performance that can be expected from a particular boiler plant of small or medium size in use in a factory, or alternatively to ascertain whether any improvement or deterioration has occurred since a previous test.

*Further advice on this matter can be obtained on application to the Ministry of Power or the National Industrial Fuel Efficiency Service or from consultants who specialize in this work. Regarding the last-mentioned, enquirers may consult the Secretary, Institute of Fuel 18, Devonshire Street, London W.1.

B.S. 845 prescribes certain conditions required for performing the test satisfactorily. In practice these conditions would not be easy to comply with in many small industrial plants. Conditions are not likely to remain constant for the full prescribed test period and 24-hour a day working is not likely in most plants. Keeping in mind these preliminary cautionary remarks, it should be understood that, in general, the rate of evaporation must be kept as steady as possible throughout the whole period of the test; once combustion conditions are set for the fuel being used it should be necessary to make only minor alterations during the test.

The ideal condition is that for twenty-four hours before the beginning of the test the load should be maintained as near as possible to that carried during the test; since in many works this is not possible, the test load should be carried for at least four hours before the start to stabilize conditions. It should be recognised that the measured efficiency may be subject to error by reason of the gain or loss of heat from the structure during the test.

Furthermore, there is a direct relationship between thermal efficiency and load in any boiler; accordingly the precision with which the load is determined is most important.

The trial should continue until the total fuel consumption per square foot of grate surface is equivalent to not less than 25 lb. for every 1 inch of fire thickness, with a minimum duration of four hours. This period is generally sufficient for the measurement of the other data with the degree of accuracy required. Thus, with a 6-inch fire, the trial should continue until 6×25 , i.e. 150 lb. of fuel, have been consumed per square foot of grate surface. At a rate of firing of 30 lb. per square foot, the duration would be at least $150/30$, i.e. 5 hours.

For at least one hour before and one hour after the trial, sufficient data are collected to demonstrate that similar and steady conditions prevailed at the beginning and end of the trial. A four-hour trial plus these two control hours is less liable to error than a six-hour trial without the control periods. The fire should be as far as possible in the same condition (thickness, etc.) at the end of the trial as at the start. With hand-fired furnaces the trial should cover one or more complete cycles from clean fires to clean fires.

With pulverized fuel, direct-fired on the unit system, four hours with two control hours are usually sufficient. Where the pulverized fuel is not fired direct from the pulverizer, either in the unit or central system, a longer period may be necessary for a correct determination of the fuel consumption. Such duration can be determined only by an examination of the plant and the possible variation of the quantity of fuel contained in the system between the point of weighing the fuel and its delivery to the furnace. The test should be of sufficient length to reduce this variation of the quantity of coal contained in the system to a percentage of the total fuel consumed, consistent with the degree of accuracy aimed at, ordinarily about 1 per cent.

COAL

The coal used for the test should be the same as that normally used. The amount used should be weighed as indicated in Chapter 27.

The coal should be sampled in accordance with B.S. 1017 (see Chapter 29) and the calorific value, together with the proximate analysis, determined by a competent chemist. When a staff chemist is not available the services of a firm specializing in this class of work should be sought.

The accuracy of the result of the test depends upon the accuracy with which the calorific value of the fuel is determined. This depends upon two factors, (a) proper sampling of the fuel and (b) determination of the calorific value. Any inaccuracy occurring in either of these factors will be directly reflected in the final result. The important part which proper sampling of the

fuel plays in the determination of boiler efficiency is not always realised; it is therefore essential that standard methods of sampling be rigidly adhered to.

SAMPLING

No matter how carefully all the other operations of a test are carried out and how accurately the results are calculated, the value of the test can be completely vitiated if the sampling has not been done correctly. It is, in fact, not too much to say that the reliability of the test depends as much on the care and accuracy with which the sampling has been done as on the accuracy of the analyst's work, if not in fact more. This point is emphasized because competent fuel technologists and consultants persistently obtain evidence of the carelessness and ignorance surrounding the important subject of sampling. If the sample has not been prepared in such a manner as to be an accurate representation of the fuel supply no amount of subsequent accurate analytical work will remedy the position. For further information regarding sampling the reader is referred to Chapter 29.

At the same time as the sample for the determination of calorific value is taken, a further sample of at least 20 lb. should be prepared for the purpose of making a sizing analysis; determination of sizing should be undertaken by the chemist. Although details of the coal sizing are not necessary to determine the efficiency at which the plant is operating, they provide information which is essential before any recommendation for improvement in the efficiency can be made. The sizing specification should be drawn up by reference to the B.S. sieve numbers.

WATER EVAPORATED

Methods of measuring water and steam by orifice plate, and water by V-notch, are described in Chapter 27.

If the weight of steam produced is taken as the weight of water fed to the boiler every care must be taken when measuring this water to see that no water is used for any other purpose, that there is no escape of water from the feed system, no leakage from pump glands or safety valves, and that water is not blown down from the boiler during the test. If the boiler is fitted with a continuous blow-down system, allowance must be made accordingly, or the blow-down must be shut off for the period of the test.

In addition to the methods of measurement given in Chapter 27, water may be weighed directly in tanks placed on weighbridges, this being the best method for small installations; or the water may be measured in calibrated tanks, the volumes at the beginning and ending of the test being corrected for temperature.

The water level in the boiler should be the same at the finish as at the start of the test.

It is desirable to determine the wetness of the steam, especially when there are no superheaters, or when superheaters are not installed on all the boilers.

TEMPERATURES

Temperatures of the following are:

Water entering economiser.

Water entering boiler.

Flue gases at exit from boiler, economiser and air heater, where fitted.

Air supply to furnace.

Air supply to air heater.

Steam temperature, where superheater fitted.

The measurement of temperature and the precautions necessary to obtain true readings are discussed in Chapter 27, and also under "Stratification",

Chapter 10. If a superheater is fitted, care must be taken to see that the thermometer records the true temperature of the steam leaving the unit. The thermometer pocket should be placed in a straight length of pipe some 2-4 feet from the superheater stop valve.

When taking the temperature of flue gases above 800° F., a suction pyrometer is recommended unless the flue is below ground level or is well insulated. Sheathed thermometers and thermo-couples give low readings where they can "see" any surfaces markedly cooler than those of the gas. The error involved may be of the order of 100 degrees for temperatures about 1,000° F. Temperature readings taken near the economiser outlet are likely to be vitiated by stratification. If it should be necessary to take readings at that position, special precautions must be taken wherever the instrument can "see" the economiser tubes. The higher the velocity of the gases at the point of measurement, the more nearly is the measured temperature likely to be accurate.

FLUE GAS ANALYSIS

The standard method of analysing flue gases during a boiler test is by use of the Orsat apparatus, the 3-bulb apparatus giving the CO₂, O₂ and CO contents of the gases. Continuous sampling is necessary and it is desirable to employ an automatic CO₂ indicator or preferably a recorder. Before and at intervals during the test these should be calibrated against an Orsat apparatus.

It is necessary once again to stress the importance of ensuring that the sample of gas withdrawn into the Orsat is a truly representative average sample. This subject is discussed in Chapters 29 and 30. The sampling pipe line from the plant to any automatic CO₂ analyser should be tested for air leakage by comparing its readings with a series of CO₂ readings obtained by means of an Orsat apparatus, first at the gas sampling point and then at the analyser.

ASHES AND RIDDINGS THROUGH GRATE

The ash should be set aside, allowed to cool and then weighed. A sample should then be taken, the same care being exercised as in taking the sample of fuel. The sample is then sent to the chemist for the determination of the combustible content.

The riddlings should always be re-fired; but if it is not practicable to do so during the test the riddlings should be added to the ash before weighing and sampling.

If the conditions are such that the ash and clinker have to be quenched before weighing, the sample should be taken during the weighing and sealed in the container to prevent loss of moisture. This is necessary to ensure obtaining the correct figure for weight and combustible content, which is calculated on a dry basis.

LOSSES

In the examples given in Tables 1 and 2, the following losses are shown in the Heat Account:

Loss due to sensible heat in chimney gases.

Loss due to unburnt CO

Loss due to combustible matter in ashes and clinkers.

Balance: radiation and other unmeasured losses, including grit emission.

The difference between the sum of these four items and 100 per cent. represents the overall efficiency of the plant on the net calorific value, thus obtained by the *indirect method*.

The latent heat in the water vapour in the flue gases is ignored, as the Heat Account is based on the net C.V. of the fuel. The sensible heat of the gases depends not only on their temperature but also on their composition, since

this affects their specific heat. The following simplified method of calculation, devised by Siegert, is used in B.S. 845:

Loss as sensible heat in flue gases, per cent. = $\frac{K (t_2 - t_1)}{\text{per cent. CO}_2 \text{ in flue gas}}$
where K=0.35 for bituminous coal
0.37 for anthracite
0.39 for coke
0.32 for oil fuel
 t_1 =temperature of air supply to furnace, °F.
 t_2 =temperature of gases leaving boiler, economiser or air heater.

The maximum error in using this simplified formula is ± 1 per cent. for temperatures of the order of 500° F. commonly met with at economiser outlets. At temperatures of the order of 1,000° F. the error rises to ± 3 per cent. It is therefore recommended that wherever possible the calculation should be made from first principles as set out in Chapter 7.

In the examples the chimney loss is the largest of the four losses, and this is almost always so in practice. It will be seen that the magnitude of the chimney loss is directly dependent upon the temperature of the leaving flue gases, and on the percentage of CO₂; a lower gas temperature or an increase in the CO₂ produces a smaller loss.

A low leaving gas temperature can be obtained by:

- (a) Installing in the first place ample heating surface of boiler and/or economiser, but in determining the size of these sections of the plant, consideration has also to be given to the appreciable increase in capital cost that results when a plant is designed for a very low leaving gas temperature.
- (b) Maintaining the heating surfaces both externally and internally in a clean condition.
- (c) Using the minimum quantity of excess air for combustion.

With plants that are in good condition and efficiently operated, losses of the following approximate order should be expected:

Loss due to unburnt CO..	..	..	Nil.
Loss due to combustible matter in ashes and clinkers	..	..	..
			Not exceeding about 2 per cent. unless the fuel burnt has abnormal characteristics such as high percentage of fines, non-caking qualities, etc., when this loss will be appreciably greater.
Balance—radiation and other un-measured losses	..	..	..
			Not more than about 6 per cent. Where conditions favour grit emission (see Chapter 11) this figure may be very much higher. It will also increase when boilers are operated on low loads.

DRAUGHT GAUGES

Draught gauges are necessary for proper control of operation, but although draught readings do not come into efficiency calculations they should be recorded as they may be required later when discussing the results.

PRESSURE GAUGES

The saturated steam pressure is the pressure of the steam in the boiler drum; superheated steam pressure is measured at the superheater outlet. Bourdon

gauges are quite suitable for this measurement, but they should be calibrated against a dead-weight pressure tester or against a calibrated master gauge. Any correction necessary should be noted and applied.

READINGS

It will usually be found that all the readings of the various instruments are reasonably steady when the boiler is tested at a constant rate of evaporation and readings need only be taken at say 15 or 20 minute intervals. In testing under working conditions (which is commonly desirable) the rate of evaporation will vary, affecting the readings of all instruments in varying degrees. Where possible, continuous records should be obtained, particularly of CO_2 content and temperature of flue gases and of boiler pressure. Where this is not practicable, spot readings should be taken at intervals not exceeding 15 minutes.

It is convenient to have readings taken by individual observers on foolscap sheets and transferred after each reading to a log sheet such as B.S. 1374 on which all readings are entered⁷. This enables a watch to be kept on the effects of any changes. The only exceptions are coal consumption and water evaporated, as it is the total of these for the whole test which matters. It is difficult to segregate coal consumption into accurate hourly periods. At the end of the test the various readings should be averaged, and corrections applied where necessary.

POWER FOR AUXILIARIES

Power taken for auxiliaries is, strictly speaking, a debit against boiler efficiency. It is the general practice not to bring this item into normal efficiency calculations. It is essential to take account of this power when it is desired to arrive at a true value of overall output and efficiency, or when comparing different types of plant. For operating purposes, it will be sufficient to set up a standard of performance for the auxiliaries and then to make a check test at reasonable intervals to find out whether the performance is deteriorating.

The consumption of steam by boiler auxiliaries should be measured with some accuracy. In particular the high consumption of steam jets is often a serious source of loss, and it is important to discover exactly how much steam is being used for this and other purposes about the boiler plant. The determination of these steam quantities demands measuring accuracy of a fairly high order. When the consumption of the auxiliaries such as fans, steam jets, and pulverized fuel equipment exceeds 1 per cent. of the heat in the coal, it must be deducted in arriving at the net efficiency.

When electrical power is used the equivalent steam consumption per hour is the input to the motors in kW. multiplied by the steam consumption per kWh. of the prime mover producing the electricity. This conversion factor will vary over a very wide range according to the size and type of the prime mover, but since, as indicated, the evaluation of the power consumed by auxiliaries is only for comparative purposes, it is convenient to adopt the conversion factor given in B.S. 845, namely, 15,000 B.t.u. per h.p. hr. or 20,000 B.t.u. per kWh.

For steam-operated auxiliaries the steam consumption can sometimes be measured without undue complications, but frequently this will hardly be practicable, and the maker's figures should then be adopted.

When steam jets are used below the fires either for cooling or for forced draught, the steam consumption can be calculated with reasonable accuracy if the diameter of the throat of the jet, and the steam pressure and temperature in front of the nozzle are known. A suitable formula is given in Chapter 8. It may be recalled that the passage of high velocity steam leads to erosion

and therefore in practice the steam consumption of jets gradually increases as nozzle wear proceeds. A watch should be kept on this wear, and as the cost of nozzles is very low, they should be renewed at reasonable intervals to keep down steam consumption.

It is usual to exclude feed pumps from individual boiler auxiliaries, for various reasons. If it is considered necessary for any reason to undertake a test of the feed pumps, then this should be carried out by means of a separate efficiency test.

GENERAL REMARKS

Consideration will reveal that the whole object of boiler testing is to compare the results being obtained with some standard. It is therefore not only desirable to have a standard of performance for the particular plant which can be set by the tests outlined earlier, but also to have detailed particulars of what has been achieved on other plants of a similar type and size.

Comparison of the results of a number of efficiency tests made from time to time on the same plant may reveal a change in performance. When a reduction in thermal efficiency is suspected or known, it may arise from one or more of a large number of causes. If the steam load for the individual tests has changed it will affect the calculated efficiency and the percentage figures for losses due to radiation. A change in actual efficiency may be due to a change in the character of the coal used. A loss due to fouling of the exterior heating surfaces, or to scaling on the water or steam sides, will be indicated by a rise in the temperature of the flue gases; this rise may be due to fouling over many sections of the boiler, or it may be confined to one section. If, for example, the economiser is at fault, the temperature of the gases entering it will be normal, while the temperature of the gases leaving it will be higher than normal; the temperature of the water leaving the economiser will then be lower than normal. Whether the loss in efficiency is due to internal or external fouling must be ascertained by visual inspection. If a change in efficiency is shown by tests, particular care must be taken to recheck the instruments used before making any major deductions from the results.

A low superheated steam temperature may be due to one or more of three causes :

(i) Fouling of the exterior surfaces, (ii) priming, (iii) Displacement of baffles.

Fouling of exterior heating surfaces may be seen in some cases by simple visual inspection; but some portions of the heating surfaces may be inspected only when the boiler is out of commission.

If priming occurs, i.e. if water is carried over from the boiler into the superheater (so that the superheater tubes become used for evaporating as well as for superheating) a fall in the steam temperature will inevitably result, the separator in the boiler must be examined. If solids are carried over with the steam from the boiler into the superheater, scale or sludge will be deposited on the inside of the superheater tubes. If this should occur attention must be given not only to the separator in the boiler, but also to the treatment of the feed water (Chapter 16).

Visual inspection will show whether all baffles are correctly located.

The quality of the combustion as indicated by the gas analysis (CO_2 and CO content) must be watched carefully, as has been indicated in Chapters 6 and 8.

Even with small plants, if mechanically fired, the efficiency should average between 70–80 per cent., and should be nearer the higher value than the lower. In large power stations average efficiencies of over 85 per cent. are achieved by installing plant that will produce a high efficiency and then arranging the equipment and operation so that all losses are kept constantly to the minimum value.

Test results (Tables 1 and 2) are set out in the manner recommended in B.S. 845, suitably adapted in Table 2 for the case of oil firing.

TABLE 1. LANCASHIRE BOILER

1. Specified Conditions and Performance			
Item.	1. Evaporation, normal load	lb./hr.	9,000
"	2. Pressure of steam	lb./sq. in.	230
"	3. Final steam temperature	° F.	675
"	4. Initial temperature of feed water	° F.	110
"	5. Class of fuel	Washed smalls.	
"	6. Overall thermal efficiency	per cent.	76
2. Particulars of Plant			
"	7. Boiler (type) Lancashire 30 feet × 9 feet, heating surface	sq. ft.	1,032
"	8. Superheater (type) downtake, heating surface	sq. ft.	282
"	9. Economiser (type) gilled tube, heating surface	sq. ft.	1,760
"	11. Method of firing	Coking stoker.	
"	12. Grate area	sq. ft.	45
"	13. Draught plant	Motor driven induced draught fan.	
3. Data from Observations, Analyses, etc.			
"	14. Duration of test	hr.	8
A. Fuel			
"	15. Description	Washed smalls.	
	Size : Through 1 in. B.S. Sieve	per cent.	100.0
	" $\frac{1}{2}$ in. " " " " " " " " " "	" "	92.4
	" $\frac{3}{8}$ in. " " " " " " " " " "	" "	82.7
	" $\frac{1}{4}$ in. " " " " " " " " " "	" "	66.9
	" $\frac{1}{8}$ in. " " " " " " " " " "	" "	46.7
	" $\frac{1}{16}$ in. " " " " " " " " " "	" "	28.8
"	16. Proximate analysis as weighed :		
	Moisture	" "	7.9
	Volatile matter	" "	29.8
	Fixed carbon	" "	57.0
	Ash	" "	5.3
			100.0
"	17. Gross calorific value as weighed	B.t.u./lb.	12,890
"	18. Net or lower calorific value as weighed	B.t.u./lb.	12,370
"	19. Fuel fired per hour	lb.	1,359
"	20. Fuel fired per hour per square foot of grate area	lb.	30.2
B. Ashes and Clinkers			
"	21. Collected per hour	lb.	81
"	22. Percentage of fuel fired		6.0
"	23. Percentage of combustible in ashes		33
C. Water			
"	24. Temperature entering economiser	° F.	109
"	25. Temperature entering boiler	° F.	261
"	26. Evaporation per hour	lb.	10,327
"	27. Evaporation per lb. of fuel as weighed	lb.	7.6
D. Steam			
"	28. Gauge pressure	lb./sq. in.	229
"	29. Final temperature	° F.	670
"	30. Heat per lb. above feed temperature	B.t.u.	1,278
E. Flue Gases			
"	31. Temperature leaving boiler	° F.	674
"	Temperature leaving economiser	° F.	416
"	32. Analysis leaving economiser:		
	CO ₂	per cent.	9.1
	O ₂	" "	10.1
	CO	" "	Nil
F. Draught			
"	33. Suction over fire	in. w.g.	0.8
"	35. Suction leaving economiser	in. w.g.	1.9
G. Air			
Item	39. Temperature of air supply to furnace	° F.	82

4. RESULTS

Item 40.	Overall thermal efficiency on gross calorific value of the fuel	per cent.	75.0
	<i>A. Heat Account Calculated on the Net Calorific Value of the Fuel</i>		
" 41.	Overall thermal efficiency	per cent.	78.5
" 42.	Loss due to sensible heat in chimney gases	" "	12.8
" 43.	Loss due to unburnt CO	" "	Nil
" 44.	Loss due to combustible matter in ashes and clinkers.. .. .	" "	2.3
" 45.	Balance—radiation, grit emitted, and other unmeasured losses	" "	6.4
			100.0

Note.—The somewhat high loss due to combustible matter in ashes and clinker is attributable to the high percentage of fines in the fuel.

TABLE 2. WATER-TUBE BOILER, OIL-FIRED

B.S. Items 1–9. Details not necessary for purpose of illustration.

Items 1-9. Details not necessary for purpose of illustration.						
Item 10.	Air heater .. .. .	..	..	..	..	Not installed.
„ 11.	Method of firing .. .. .	..	..	..	..	Pressure jet.
„ 12.	Number of burners .. .. .	..	..	..	..	4
„ 13.	Draught plant .. .. .	..	..	..	..	forced draught calculation.
„ 14.	Duration of test .. .. .	..	..	..	..	hrs. 8
<i>A. Fuel</i>						
„ 15.	Description .. .. .	..	..	..	..	Industrial oil fuel.
„ 16.	Analysis of fuel:					
	Moisture .. .. .	..	..	..	..	per cent. 0.5
	Hydrogen .. .. .	..	..	..	..	„ „ 11.5
	Carbon .. .. .	..	..	..	..	„ „ 85.0
	Sulphur.. .. .	..	..	..	..	„ „ 3.0
Total						100.0
Ash						0.04
„ 17.	Gross or higher calorific value .. .. .	..	..	..	..	B.t.u./lb. 18,750
„ 18.	Net or lower calorific value as weighed .. .. .	..	..	..	..	B.t.u./lb. 17,600
„ 19.	Fuel fired during test .. .. .	..	..	..	..	gal. 1,354
	Temperature of fuel in storage tank .. .. .	..	..	..	..	° F. 90
	Sp. gr. of fuel at storage temperature .. .. .	..	..	..	..	0.928
	Fuel fired (total) .. .. .	..	..	..	..	lb. 12,565
„ 20.	Fuel fired per hour .. .. .	..	..	..	..	lb. 1,571
<i>B. Ashes and Clinkers</i>						
„ 21.	Collected per hour .. .. .	..	..	..	..	} Not applicable.
„ 22.	Percentage of fuel fired .. .. .	..	..	..	..
„ 23.	Percentage of combustible .. .. .	..	..	..	..
<i>C. Water</i>						
„ 24.	Temperature entering economiser .. .. .	..	..	..	..	° F. 142
„ 25.	Temperature entering boiler .. .. .	..	..	..	..	Not required for purpose of illustration.
„ 26.	Evaporation per hour .. .. .	..	..	..	..	lb. 20,152
„ 27.	Evaporation per lb. of fuel .. .. .	..	..	..	..	lb. 12.8
<i>D. Steam</i>						
„ 28.	Gauge pressure .. .. .	..	..	..	..	lb./sq. in. 195
„ 29.	Final temperature .. .. .	..	..	..	..	° F. 530
„ 30.	Heat per lb. above feed temperature .. .. .	..	..	..	..	B.t.u. 1,173.5
<i>E. Flue Gases</i>						
„ 31.	Temperature leaving economiser .. .. .	..	..	..	..	° F. 400
„ 32.	Analysis leaving economiser :					
	CO ₂ .. .. .	..	..	..	..	per cent. 11.0
	O ₂ .. .. .	..	..	..	..	„ „ 6.3
	CO .. .. .	..	..	..	..	„ „ Nil
<i>F. Draught, and G. Air</i>						
Items 33 to 38 inclusive .. .. .	..	..	..	..	..	Not required for this calculation.
Item 39.	Temperature of air supply to furnace .. .. .	..	..	..	..	° F. 60

RESULTS

Item	40. Overall thermal efficiency on gross calorific value of the fuel per cent.	80.3
	<i>A. Heat Account Calculated on the Net Calorific Value of the Fuel</i>	
41. Overall thermal efficiency per cent.		85.5
42. Loss due to sensible heat in chimney gases		9.9
43. Loss due to unburnt CO		Nil
44. Loss due to combustible matter in ashes and clinkers		Not applicable.
45. Balance: radiation and other unmeasured losses, including unburnt fuel		4.6
		100.0

B. Net Overall Thermal Efficiency

Not required for this calculation

Table 3 summarizes the results obtained on two plants, one efficient and the other inefficient, for purposes of comparison. It should be noted that these Heat Accounts, giving as they do credit for the latent heat in the moisture in the flue gases (Items 2, 3), are based on the Gross C.V. of the coal.

TABLE 3

	<i>Efficient plant</i>		<i>Inefficient plant</i>	
	<i>B.t.u.</i>	<i>Per cent.</i>	<i>B.t.u.</i>	<i>Per cent.</i>
(1) Heat absorbed by water and steam in boilers, superheaters and economisers ..	9,925	79.40	7,588	60.70
(2) Heat loss due to moisture in coal ..	24	0.19	29	0.23
(3) Heat loss due to water from combustion of hydrogen	560	4.48	672	5.38
(4) Heat loss due to moisture in air ..	40	0.32	49	0.39
(5) Heat loss due to dry chimney gas ..	1,312	10.50	2,400	19.20
(6) Heat loss due to incomplete combustion of carbon	—	—	600	4.80
(7) Heat loss due to unconsumed combustible in ash	225	1.80	525	4.20
(8) Heat loss due to unconsumed hydrogen, and hydrocarbons, radiation, and unaccounted for	414	3.31	637	5.10
	12,500	100.00	12,500	100.00

Item (1) should be sub-divided to show the heat absorbed by the boilers, superheaters and economisers separately. Typical values are as follows:

	<i>Efficient plant</i>		<i>Inefficient plant</i>	
	<i>B.t.u.</i>	<i>Per cent.</i>	<i>B.t.u.</i>	<i>Per cent.</i>
(1a) Heat absorbed by water and steam in boiler	7,837	62.7	6,300	50.40
(1b) Heat absorbed by steam in superheaters ..	688	5.5	525	4.20
(1c) Heat absorbed by water in economisers ..	1,400	11.2	763	6.10
	9,925	79.4	7,588	60.70

REPORTING BOILERHOUSE PERFORMANCE TESTS

Different firms may prefer different forms for reporting their tests, to suit their individual requirements. B.S.I. 1374, already referred to, will probably be found suitable in most cases.

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- ⁴ Compiled from data supplied by W. A. MOORSHEAD (private communication).
- ⁵ Compiled from data from Sarjant and Barnes, *Trans. Open Hearth Conf.*, 1938, p. 238.
- ⁶ B.S. 845. Code for Commercial Acceptance Tests for Steam Boilers. 1939, London. British Standards Institution. (Under revision.)
- ⁷ B.S. 1374. Log sheets for Steam Boiler Plants. 1947. London, British Standards Institution

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NOTE

The following corrections should be made in Figs. 3, 6 and 7 (reproduced from the First Edition):—

Fig. 3, lower portion—under FLUE—for 1.1 read 1.2, and for 1.6 read 1.7. In the channel for ECONOMISER the figure 1.0 appears twice; delete one entry.

Fig. 6, for 55.0 read 54.9.

Fig. 7 top portion—HEAT LOSSES IN REGENERATOR—for 17.7 read 7.9.

CHAPTER 27

INSTRUMENTATION

EFFICIENCY in the use of fuel can be achieved and maintained only by the careful control of the conditions under which it is consumed to produce energy in the form of heat or power. To control any physical condition, a primary requirement is that its value be known; to obtain this information an appropriate measurement is required. This chapter is confined to the measurements that are most important for the efficient operation of fuel-using plant, boilers for generating steam or hot water, kilns, steel furnaces, metal treatment furnaces and so on. These include measurements of pressure, temperature, rate of flow, smoke density and gas composition. Associated with these measurements are the transmission of their values over a distance, and distant recording instruments.

The rapid expansion of instrumentation in recent years has led to the appearance of a wide range of measuring equipment for sensing and registering the value of virtually all physical variables encountered in industry. Even when the range of measurements is restricted to the above list, a detailed description of all the types of instruments that can be used in various circumstances would be beyond the scope of one chapter, which must, therefore, be limited to considerations of the general principles involved, along with brief notes on installation and maintenance. Details of specific equipment can readily be ascertained from catalogues and other literature issued by the various manufacturers, a valuable additional source of technical information.

An installation for measuring the value of a physical variable can generally be divided into two parts (*a*) the detecting element—which senses the value of the variable under consideration—and (*b*) the measuring element—which registers this value in appropriate units.

As the form of the detecting element is determined by the nature of the physical variable, there are a number of these basic elements. The feature common to them all is that whatever the nature of the physical variable, they express its value in terms of a proportionate mechanical displacement, fluid pressure or electrical quantity. In spite of the fact that the mechanical details vary within wide limits, there are only three basic measuring elements responsive, respectively, to (*a*) a displacement, (*b*) a pressure or (*c*) an electrical input. When the variable being measured is a mechanical displacement, a pressure, or an electrical quantity, in most instances the detecting element is not required.

The general trend in instrument design is so to restrict the range of measuring elements that one particular instrument can be used without modification, or with the addition of a few standard parts, to operate with a wide range of detecting elements designed for specific measurement. The measuring element can give an indication on a scale, a recording on a paper chart and, if need be, an integration on a *counter*, of the value of the physical variable, or any combination of these three forms of presentation.

PRESSURE MEASUREMENT

Instruments for measuring pressure may be classified as (*a*) “wet” type and (*b*) “dry” type instruments.

Other types of pressure-measuring equipment are available, such as strain gauges and heated wire gauges (for extremely low pressures) but these are not within the scope of this work.

"WET" TYPE INSTRUMENTS

These are restricted to the measurement of low gauge pressures and suctions (sub-atmospheric pressures) of a few pounds per square inch.

A common application is for the measurement of draught and furnace air pressure.

In its simplest form, the "wet" type pressure measuring instrument consists of a glass U-tube partly filled with liquid. (Fig. 1). Pressure or suction applied

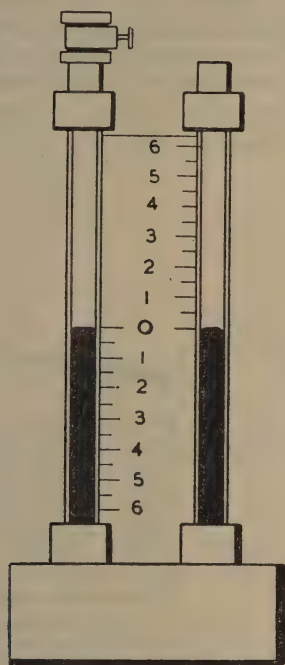


FIG. 1. Double-tube manometer.

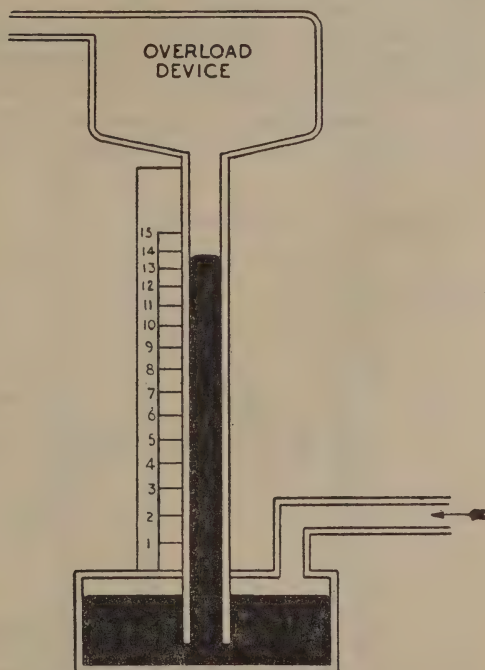


FIG. 2. Single-tube manometer.

to one limb of the U-tube produces a displacement of the manometer liquid. The vertical difference in level between the menisci in the two limbs is a measure of the pressure applied. In order to confine the displacement of the liquid to as far as possible one limb, the other is made of large cross-sectional area, thus forming a reservoir—the reservoir may be made of metal. (Fig. 2). The nature of the manometer liquid depends on the application. For low air and gas pressures, oil may be used and the glass tube may be inclined to increase the displacement of the liquid and thus give more accurate readings. For liquid pressures and higher ranges of air and gas pressures, mercury is used as the manometer liquid.

The simple manometer can give only local indication of pressures and it is inevitably rather fragile. For indication on a dial and also for recording pressure variations on a chart, float-operated mercury-filled U-tubes, sealed bell and ring balance type instruments are available, but since these are primarily used for differential pressure-type flow metering, they are dealt with under **FLOW MEASUREMENT** below (p. 736).

"DRY" TYPE INSTRUMENTS

These comprise instruments in which the applied pressure causes displacement of a diaphragm or similar element, the magnitude of this displacement being a measure of the pressure.

For measuring low pressures (down to a fraction of an inch water gauge below or above that of the atmosphere), a slack and extremely flexible diaphragm, e.g. of gold beater's skin can be used. The pressure or suction is applied to one side of the diaphragm, the other side being spring-loaded. The diaphragm forms the seal between the source of pressure and the spring, so that the amount of deflection for a given pressure is determined by the strength of the spring. Through a very light magnifying movement, the deflection is transmitted to an indicating pointer (Fig. 3). Pressure-measuring instruments

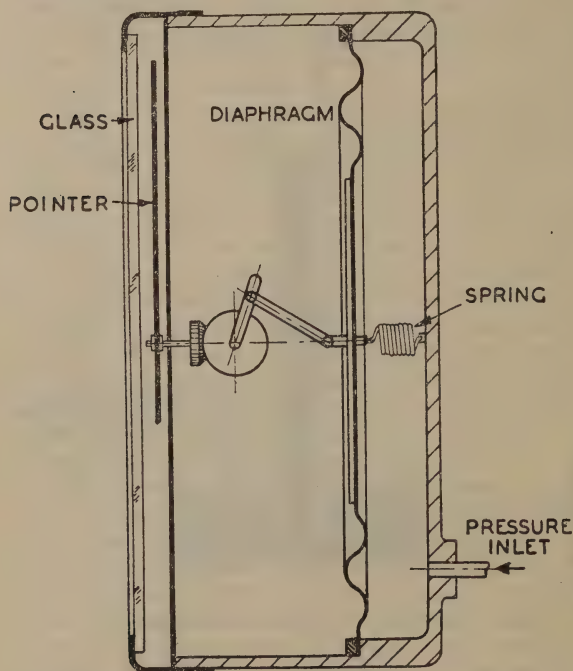


FIG. 3. Single-diaphragm pressure-measuring instrument.

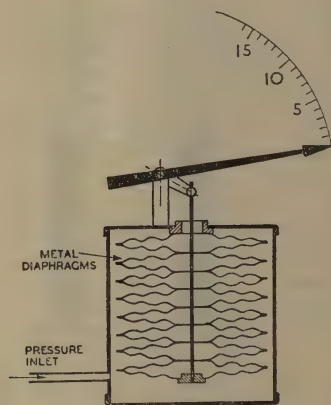


FIG. 4. Multi-diaphragm pressure-measuring instrument.

of this type are limited to gases, and the design with an edgewise scale and suitable for wall or panel mounting is widely used in steam generating and similar plant.

Another form of gauge, also for measuring low pressures, uses corrugated metal diaphragms; when a number of diaphragms are used the assembly may be likened to a metal concertina. When pressure is applied to the diaphragm assembly, the resultant deflection is determined by the flexibility of the unit (Fig. 4). Gauges of this type are available for recording the pressure (or suction) on a paper chart and are suitable for pressures ranges varying from a few inches w.g. above or below the prevailing atmospheric pressure to $+ 50$ lb./sq.in., or 'absolute vacuum'.

A modern development is the bellows unit, i.e. a corrugated metal cylinder of beryllium-copper or similar alloy. This is usually spring-loaded, the amount of deflection for a given pressure being determined by the combined resistances

of the bellows and of the spring. The range of maximum pressures is of the order of $\frac{1}{2}$ to 100 lb./sq. in., and the unit can be used for measuring both liquid and gas pressures.

For higher pressures, up to the maximum encountered in industrial practice, the Bourdon tube element is used. This consists of a tube of elliptical cross section bent into the shape of the letter 'C'. For general purposes this is made of phosphor bronze or beryllium-copper. The free end of the tube is sealed; the other end is anchored and the pressure to be measured is applied to its interior at this end. Pressure applied to the interior of the tube tends to change its shape from elliptical to circular and, in so doing, to straighten the tube. The resultant movement of the free end of the tube, *via* a sector and pinion or similar mechanism, is calibrated to indicate or record in terms of pressure (Fig. 5). In another design, the tube is wound into the form of a helix. This gives a larger displacement of the free end of the unit and the pen or pointer may be fixed *direct* on to the free end of the tube. (See Fig. 9, page 726).

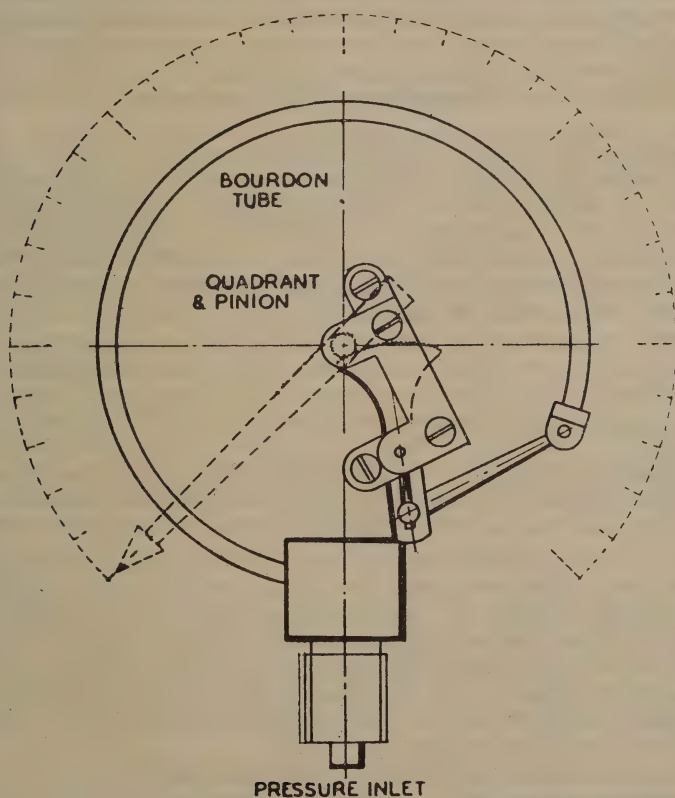


FIG. 5. Bourdon tube pressure measuring instrument.

An instrument that could with advantage be more widely used on small steam raising plant is the "critical pressure" gauge. This is for measuring not the critical pressure of the steam but some preferred or desired pressure, with a false zero gauge, so as to obtain a higher reading accuracy and an obvious indication when the actual pressure is not the desired pressure. In relation to its value as an aid to efficiency it is probably the least expensive of instruments.

It consists of a loaded diaphragm, adjusted to give centre-of-scale reading at the selected preferred steam pressure. Full scale deflection is given by a

change in pressure of a few pounds per square inch above or below the selected value, so that the gauge gives an immediate indication of changes in steam demand. The gauge is protected against possible damage from pressure variations beyond its scale range.

For certain applications, as for example, evaporators, it is important to maintain a pre-determined absolute pressure. A common design of absolute pressure gauge is one having two pressure elements, e.g. two bellows units, connected in opposition. One unit is evacuated so that its expansion and contraction are influenced by changes in atmospheric pressure; the other is subjected to the pressure being measured. The displacement of the element is then proportional to the atmospheric pressure *plus* the gauge pressure. This displacement is registered in the appropriate units.

The installation of a pressure measuring device should present no difficulty provided a few simple rules are observed. When measuring the pressure of a gas in motion, e.g. air flow through a duct, the plane of the pressure tapping must be at right angles to the direction of flow, otherwise a measurement will be obtained of the static pressure *plus* or *minus* a pressure which is a function of the velocity head. For a similar reason, a parallel portion of the duct should be selected for the point of measurement. This applies to liquid measurement also.

It is important to keep the impulse pipe clear so that the pressure can be accurately transmitted from the point of measurement to the measuring element. This pipe should, therefore, be laid in such a manner that it does not become choked with scale; accumulated moisture (in gas measurement) or air pockets (in liquid measurement), must also be avoided, especially when low gauge pressures are being measured. Dust and moisture are liable to give trouble when dealing with hot flue gases.

When dust and moisture are expected near to the tapping point, an impulse pipe of generous proportions should be used, and facilities for cleaning the bore without undue trouble should be provided. The pipe should slope upwards from the tapping point to allow any moisture condensed from the cooled gas to drain back.

Where possible, gas pressure tappings should be made in the top of a horizontal conduit, and liquid pressure tappings in the side. For obvious reasons, pressure tappings should never be made in the invert of a pipe or conduit.

For liquid pressure measurement, the impulse pipe will be charged with the liquid. Therefore, if the gauge is mounted at a level above the tapping point, it will register the pressure at the tapping point, *minus* the pressure due to a column of the liquid equal in height to the vertical distance between the tapping point and the gauge. The converse is true if the gauge is mounted below the tapping point. This discrepancy may be negligible when a high liquid pressure is being measured, but in other circumstances it becomes significant and must be taken into account.

No instrument should be subjected to unduly high temperatures. When dealing with hot fluids adequate cooling is, therefore, required between the tapping point and the gauge; the impulse pipe itself may be adequate for this purpose. In steam pressure measurement, the impulse pipe must be charged with condensate and a water-filled syphon or similar device must be mounted near to the gauge. A gauge should *never* be too hot to handle with comfort. In theory at least, a wet type gauge of the mercury-in-glass type could be used for low pressure steam measurement, but there are obvious risks. For steam pressure measurement, a dry-type gauge of suitable form is, therefore, invariably used.

A dry-type gauge should never be over-stressed. The instrument selected

should, therefore, be one with a maximum reading about 50 per cent. higher than pressure normally to be measured. Dry type draught gauges are particularly susceptible in this respect—they should not be “tested” by blowing into them. “Work within the middle of the range” is often a good precept, though some instrument dials are so calibrated as to be important exceptions to such a rule. In common with all other measuring instruments, pressure gauges should be mounted in a position free from vibration. If the gauge is of the indicating pattern, its function is to facilitate minute-to-minute plant operation; it should, therefore, be placed in a readily visible position. If of the recording pattern, it should be located at a point where the atmosphere is free from dust and dirt because the case has to be opened at regular intervals for changing the chart, etc.

For ease of maintenance, there should be an isolation valve at the tapping point and a valve immediately adjacent to the gauge. The latter may be used to damp down pressure pulsations. For draught measurement and similar applications, it is useful to fit a three-way cock at the gauge to enable the gauge to be vented to the atmosphere for checking purposes.

TEMPERATURE MEASUREMENT

It is convenient to group temperature measuring instruments into three main classes, viz: (a) expansion types, (b) electrical types, (c) radiation types. Other methods of temperature measurement, e.g. refractory cones for furnaces are not considered here. (See Chapter 23.)

EXPANSION THERMOMETERS

All these instruments employ, in one form or another, the physical property, possessed by most substances, of expanding or contracting with rise or fall of temperature. In the case of a gas, if its volume is kept constant, its pressure changes with temperature.

Solid expansion thermometers.

These instruments are operated by the change in length of a metal rod or the deflection of a bi-metallic strip. Their use is generally limited to simple types of thermostats and similar equipment, and they are rarely used in industry for the straightforward measurement of temperature.

Liquid expansion thermometers

The simplest of these instruments is the familiar mercury-in-glass thermometer. Special thermometers of this form are a sub-standard for temperature measurement and may be used, with due precautions, for checking the accuracy of other types of temperature measuring instruments. Mercury-in-glass thermometers are widely used in industry, over moderate temperature ranges, for routine indications of temperature, and various robust forms, e.g. sheathed in metal, are available as sub-standard or reference instruments for occasional measurements. Alcohol, toluene, and xylene are also used as alternatives to mercury for filling thermometers, especially, in the case of alcohol, for temperatures below that at which mercury freezes (*minus* 38° C.). The limitations of their use to indicate temperatures, and their inherent fragility, are important practical disadvantages of instruments of this type.

For recording purposes, there are other forms of fluid-filled systems. Basically they all consist of a temperature-sensitive element, which is formed by a metal “bulb”, joined to the measuring element by a length of capillary tube. Fig. 6 shows some types of bulb commonly used.

The liquid-sealed system very widely used in industry is the mercury-in-steel thermometer. The measuring element consists of a Bourdon tube gauge,

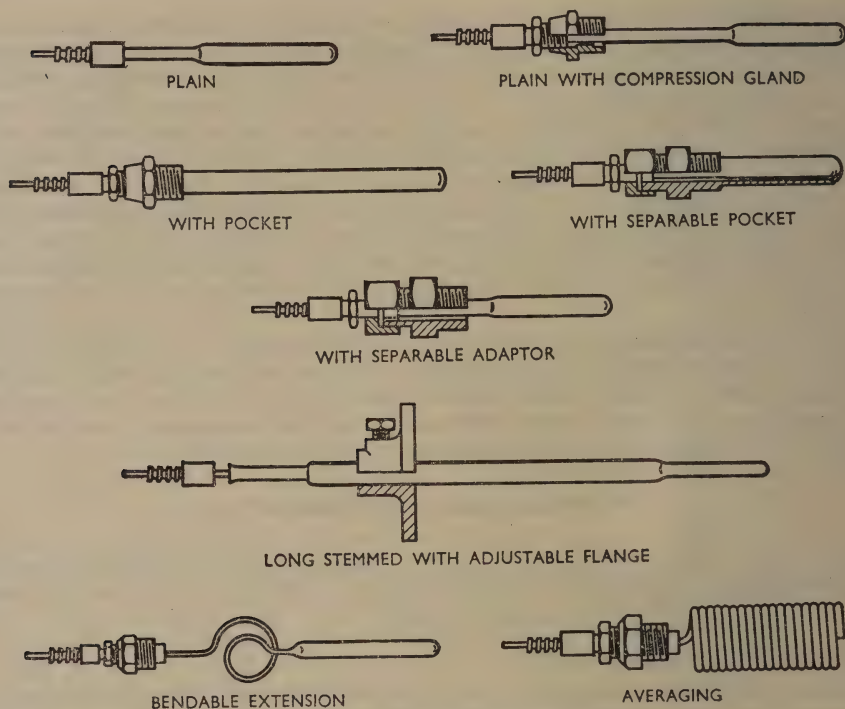


FIG. 6. Types of thermometer bulbs.

which acts as a volume measuring device (Fig. 7). The purpose of the measuring element is to register the change in volume of the mercury in the bulb, in terms of temperature, without being influenced by any change in volume of

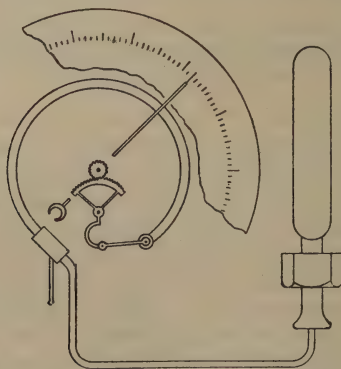


FIG. 7. Liquid expansion thermometer.

the mercury within the capillary tubing, due to changes in ambient temperature. To minimize this temperature effect, the capillary tubing is of extremely fine bore, so that the volume of the mercury it contains is very small compared with that contained in the bulb. Various methods are used to obtain automatic ambient temperature compensation. For example, a wire of low expansion material may be run throughout the length of the capillary tube. The diameter of the wire and bore of the capillary are so proportioned that, with

change in temperature, the change in volume of the mercury equals the change in the free space in the capillary. Errors due to the temperature variation of the measuring element itself can also be compensated for, e.g. by introducing a bi-metallic strip into the movement.

The mercury is introduced into the system under high pressure. This increases the general consistency of the readings, and indirectly reduces "head" error resulting from the difference in level between the measuring and detecting elements, i.e. the error due to the weight of the column of liquid between these two points. Any head error is usually insignificant, but allowance can be made for this if necessary.

When liquid used for filling is one other than mercury, the coefficient of expansion of the liquid is generally greater. In such cases the accuracy of registration is influenced to a greater degree by temperature changes of the capillary tube, especially when the "bulb" is small and the capillary tube long.

Constant volume gas thermometers

The general principle of construction of these thermometers is the same as for liquid expansion thermometers. The system is filled with an inert gas and the measuring element operates as a true pressure measuring device, since it registers the change in pressure of a constant volume of gas.

The effect of temperature changes of the capillary system increases as the temperature of the bulb rises, so that only partial compensation for this effect is possible, e.g. by a second capillary run adjacent to the main one and connected not to the bulb but to a second pressure measuring element, e.g. Bourdon tube. The two pressure measuring elements are linked by a differential lever operating the registering mechanism (Fig. 8). This registers, in terms of temperature, the difference in the gas pressures within the two systems.

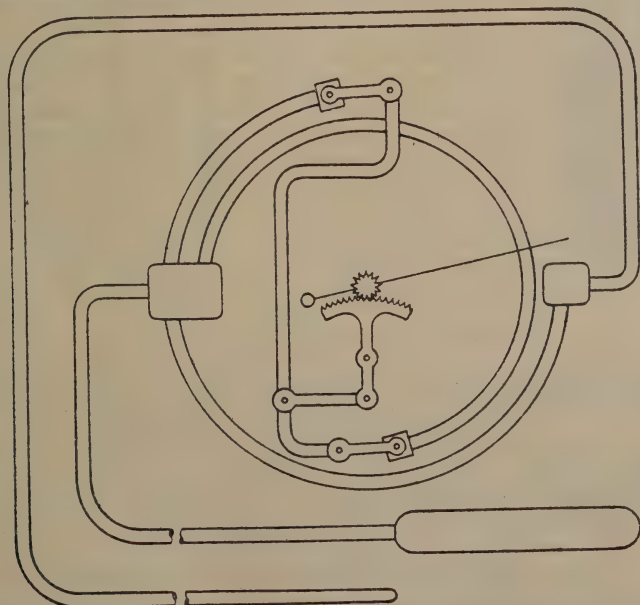


FIG. 8. Constant volume gas thermometer with automatic compensation for ambient temperature variation.

Constant volume gas thermometers are not subject to any head error, but it may be necessary to correct for the altitude above sea level. Fluctuations in

the day-to-day barometric reading are usually sufficiently small to be ignored but if desired can be corrected by adjustment of the zero of the gauge.

The advantage of gas thermometers over the liquid expansion types is that they can be used to measure the lowest temperatures encountered in industry.

Vapour pressure thermometers

In these, the same form of system is used as in the other fluid-filled systems already described, i.e. a bulb and a pressure-measuring element connected by a capillary tube. In this instance, however, the bulb is partly filled with a volatile liquid. Change in temperature of the bulb causes a corresponding change in pressure of the saturated vapour above the liquid, this pressure being registered by the measuring element in terms of bulb temperature (Fig. 9). Among the volatile liquids used are methyl chloride and toluene.

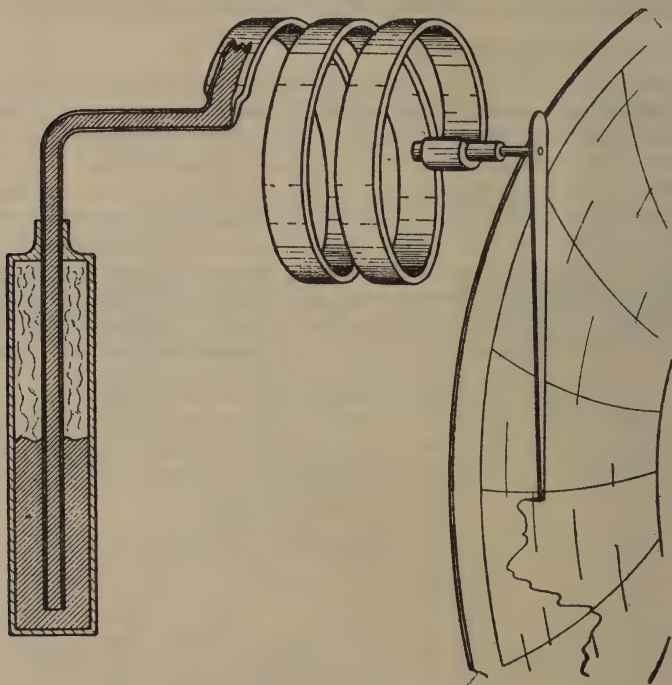


FIG. 9. Vapour pressure thermometer.

The nature of the filling medium is determined by the maximum and minimum temperatures that are to be registered by the thermometer.

Vapour pressure thermometers have certain characteristics resulting from the fact that the system is filled with a combination of liquid and vapour. For example, if the measuring element is mounted below the bulb and its temperature is lower than that of the bulb, the capillary and pressure responsive element will be filled with liquid, so a head error is introduced. When measuring temperatures that fluctuate from slightly above to slightly below that of the capillary and the measuring element, sluggish operation results owing to the time required to re-establish equilibrium of the liquid/vapour system; sudden cooling causes "kicks" in the temperature registration. These, and similar phenomena, make it desirable to specify exact operating conditions before ordering a thermometer of this description.

Change in barometric pressure due to altitude can introduce an appreciable error, but this and the head error can be corrected by a zero adjustment when installing. Subsequent corrections for day-to-day barometric pressure fluctuations are made in the same manner. Depending on temperature range and nature of the filling medium, the temperature scale tends to open out and become more uniform towards the higher temperature end of the scale, and any re-setting of the zero after installation can be done only if no mechanism has been introduced into the measuring element to open out the scale over the lower part of the range.

The main characteristics of the expansion type thermometers are given in Table 1.

TABLE 1
CHARACTERISTICS OF EXPANSION THERMOMETERS

Type of Equipment	Application	Overall industrial Temperature range	Distant reading
Metal expansion ..	Gases	0 to +400°C. ..	Not suitable
Liquid in glass ..	Solids and fluids ..	− 200°C. to +500°C.	Not suitable
Liquid in steel ..	Solids and fluids ..	0 to +600°C. ..	Up to 200 ft.
Gas expansion ..	Liquids	0 to +550°C. ..	Up to 200 ft.
Vapour pressure ..	Solids and fluids ..	− 20°C. to +350°C.	Up to 200 ft.

The measuring element is usually provided with a circular scale or circular chart.

When installing fluid-filled temperature measuring equipment, it is of paramount importance to give adequate protection to the capillary tube against accidental damage and mechanical shock. It should, therefore, be carefully supported throughout its length. The essential point is that there must be no possibility of relative movement between the bulb and the capillary tube—not always an easy matter to ensure in practice. Particular care should be given to the capillary at its junction with the bulb which should not be strained in any way. Sufficient length of capillary should be provided to enable the bulb to be withdrawn from its pocket, or other form of mounting, for examination. Any damage to the capillary renders the equipment useless, and it must then be returned to the supplier for repair.

In view of the ambient temperature variation effect, a path for the capillary should be selected that does not lie through high or low temperature zones or zones subjected to extremes of temperature. These remarks apply to the positions of exposed portions of the measuring element also.

Apart from standard routine maintenance required by all measuring elements, particularly recorders, little care and attention are required by equipment of this type, though the accuracy of temperature registration of the system should be checked at regular intervals.

ELECTRICAL THERMOMETERS AND PYROMETERS

These may be sub-divided into (a) Resistance thermometers and (b) Thermoelectric pyrometers.

Resistance thermometers

The basic principle of operation of resistance thermometers is the change of

the resistance of a conductor to the passage of an electric current with change in temperature. The detecting element is a wire, usually of platinum or nickel, and the measuring element is an electrical instrument for measuring the electrical resistance of the detecting element and registering this in terms of temperature.

The basic electric circuit for measuring the resistance of the detecting element is the Wheatstone bridge energized from an external source, e.g. an accumulator. The detecting element forms the variable resistance, the other three resistances being constant. The current flowing between the opposite corners of the bridge is related to the resistance of the detecting element, and so to its temperature, and is registered in terms of temperature by a moving coil instrument (Fig. 10). In practice, modifications are made to the circuit to compensate for variations in the supply voltage and for errors introduced by change in resistance of the cable connecting the detecting element to the instrument caused by variations in ambient temperature. Among the systems

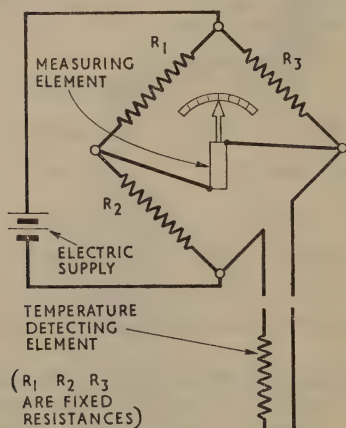


FIG. 10. Basic wiring diagram for electric resistance thermometer.

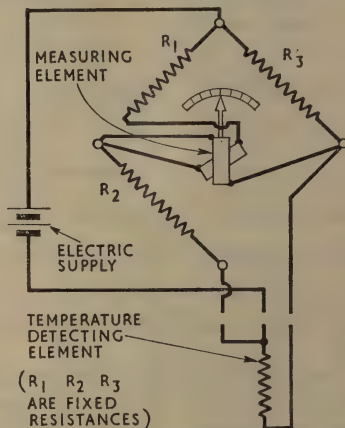


FIG. 11. Basic wiring diagram for electric resistance thermometer with automatic compensation for voltage and ambient temperature variation.

adopted are the use of a three-core cable connecting the two parts of the equipment, which compensates for ambient temperature variations (Fig. 11), and a *cross-coil* type of instrument for registering the temperature, thus obtaining compensation for supply voltage variations. In the cross-coil type of instrument (see Fig. 11) a second, control, coil is used in conjunction with the deflection coil. Any change in supply voltage has a corresponding effect on the force exerted by the control coil, so that no change in pointer deflection is obtained for change in supply voltage. These instruments are of the direct deflection type.

To obtain a powerful output, a *null balance* method may be used whereby, by the use of an external source of power, the instrument automatically and continuously adjusts the resistances of one or more of the three arms of the bridge, so that at all times there is no current flow between the opposite corners of the bridge. The mechanical displacement required to maintain this state of electrical balance is registered in terms of temperature. More detailed consideration of the operation of null-balance instruments will be found under **TRANSMISSION SYSTEMS** below (p. 766).

To protect the wire of the detecting element from mechanical damage, and corrosive action, etc. of the gas or liquid whose temperature it is to measure, the wire is wound on a bobbin, e.g. of a refractory material for temperatures

above 200° C. (Fig. 12), and is enclosed in a sheath, the bottom end of which is sealed. The unsealed, i.e. "cold," end of the sheath is provided with a junction box from which the cable is led to the instrument.

RESISTANCE WIRE

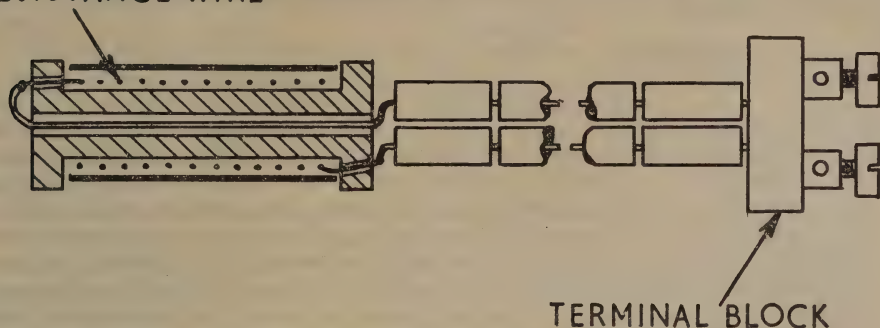


FIG. 12. Construction of a resistance thermometer temperature-sensitive element.

A variety of patterns of measuring elements are available for both wall and panel mounting. In both direct deflection and null balance forms, circular and edgewise indicators and recording instruments with circular or roll charts are available.

A feature particular to all classes of electrical temperature measuring equipment is that since the connecting link between the detecting and measuring elements is an electric cable, it can easily be disconnected and replaced by another. One measuring element can thus be used to register the temperature at a number of distant points, either by manual selection or, in the case of recording, by the automatic selection in a pre-determined sequence. In manual selection for taking spot readings, the number of detecting elements that can be used with one instrument is virtually unlimited. In the case of recording, the automatic selection is limited to a dozen or so points. For industrial use, resistance thermometers are not recommended for temperatures above 600° C.; for higher temperatures, the thermo-electric principle is to be preferred.

Thermo-electric pyrometers

These instruments consist basically of a circuit of two dissimilar metals or alloys fused together at each end. When one end, the "hot junction," is subjected to a high temperature, an electromotive force is generated proportional to the difference in temperature between the hot junction and the other, "cold," junction. The current resulting from the e.m.f. is measured by a galvanometer or similar electrical instrument located at or near the cold junction. The two wires form a *thermocouple*, and the selection of the alloys or metals to be used is influenced by a number of factors, such as resistance to high temperature, corrosion and oxidation, and temperature/e.m.f. relationship. Relatively few metals and alloys are suitable for making thermo-couples. There are two classes of thermocouple for industrial use—base metal for temperatures up to about 1,200° C. and rare metal for temperatures up to 1,500° C.

For industrial work, the thermocouple is constructed on the lines shown in Fig. 13 and is contained in a protecting sheath, the outer end of which carries a terminal box. The connecting leads from the terminal box to the cold junction may be of the same material as the thermocouple, but to save expense, especially where a considerable length is involved, *compensating cable* having the same temperature/e.m.f. characteristic as the thermocouple over the limited temperature range to which it is subjected, may be used for making

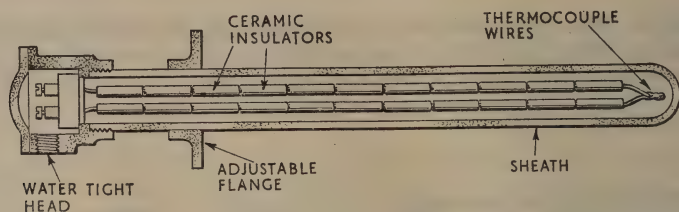


FIG. 13. Construction of a thermocouple.

the connection to the cold junction. The cold junction should, of course, be located away from the heated zone. For the connection from the cold junction to the measuring instrument standard copper cable may be used. The cold junction may be maintained at a constant known temperature, or the instrument reading may be corrected for the actual cold junction temperature (Fig. 14). The most satisfactory arrangement is that in which the cold junction is located within the instrument with automatic compensation for cold junction temperature, e.g. bi-metallic compensation in a direct deflection type instrument.

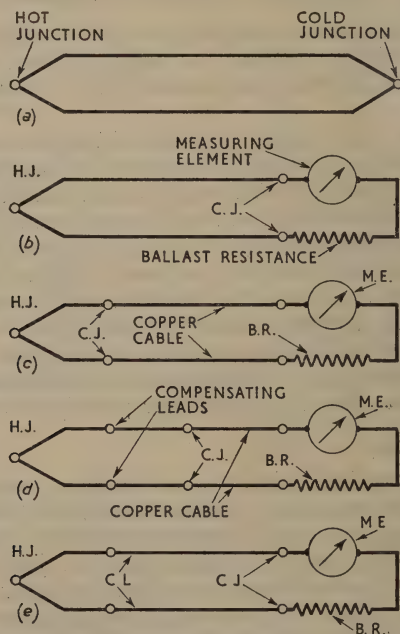


FIG. 14. Development of the thermo-electric pyrometer circuit.

Direct deflection type indicating and recording instruments are available. Alternatively, there is null balance pattern of instrument, in which a potentiometric circuit is used, the e.m.f. generated by the thermocouple being continuously balanced against a constant e.m.f. from an external source, e.g. a dry battery. The amount of adjustment of the slidewire resistance to preserve electrical balance is a measure of the hot junction temperature, and is registered in terms of temperature. The potentiometer circuit would be arranged to give automatic cold junction temperature compensation.

For temperatures not above about $500^{\circ}\text{C}.$, a mild steel sheath may be used, while for temperatures up to $900^{\circ}\text{C}.$, specially treated steel or nickel chromium alloy is required. Above $900^{\circ}\text{C}.$, refractory materials should be used. Rare

metal thermocouples are susceptible to contamination by metal vapours, and impermeable refractory sheaths should be used for temperatures above about 500°C. To give mechanical strength, the refractory sheath may be protected by an outer one of metal or refractory, but at the expense of increasing the time response of the hot junction of the thermocouple to change in temperature.

The length of service of thermocouples depends on the work they are used for—if working below the normal maximum temperature a continuous working life of 1,000 hours may be expected, increasing to say 2,000 hours or even more when working at appreciably lower temperatures. Therefore, the condition of thermocouples must be checked at regular intervals in accordance with experience.

To prevent errors due to radiation from neighbouring surfaces, e.g. the walls of a flue, when measuring gas temperatures the suction pyrometer may be used. Essentially it is an open-ended tube containing a bare thermocouple surrounded by radiation shields. This assembly is inserted into the duct or flue and a sample of the gas is continuously drawn through it. The gas velocity is increased until no change is observed in the measured temperature. There are a number of designs of this particular form of equipment (Fig. 15). The method cannot be used by an inexperienced observer.¹

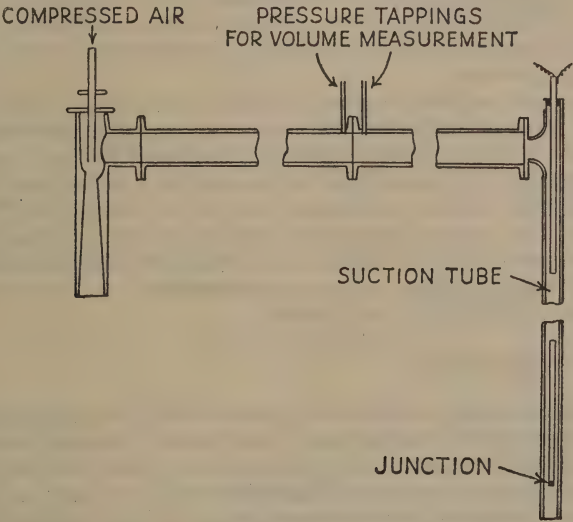


FIG. 15. Suction pyrometer.
(A. Schack, *J. Inst. Fuel* XII, S80, 1939)

A summary of the characteristics of electrical temperature measuring instruments is given in Table 2.

TABLE 2.
CHARACTERISTICS OF ELECTRICAL TEMPERATURE MEASURING
INSTRUMENTS.

Type of Equipment	Application	Overall industrial temperature range	Distant reading
Electrical resistance	Solids and fluids	– 240° C. to + 600° C.	Suitable
Base metal thermocouple	Solids and fluids	– 200° C. to + 1,100° C.	Suitable
Rare metal thermocouple	Solids and fluids	0° C. to + 1,450° C.	Suitable
Suction pyrometer	Gases	According to construction	Not generally suitable

Because of the low e.m.f. and currents involved in equipment of this type the electrical circuit should be handled and protected with special care. High resistance at joints in the circuit can cause faulty registration, so the number of connections in the circuit should be kept to the minimum possible. Junction boxes and plug connectors should preferably not be used, and joints and connections should be soldered. The accuracy of thermoelectric pyrometers of the null balance form is not affected by circuit resistance variation, which affects only the sensitivity. The connecting cable must be protected from oxidation and corrosion, and it is of vital importance that it be protected also from stray electrical leakage from nearby power or lighting circuits.

A path should be selected for the cable which will keep it away from high temperature or damp zones. If damp zones cannot be avoided, lead-covered cable, suitably supported, may be used. In hot dry locations, a woven asbestos covering may be used. The insulation between the cores must be of a high order—that normally used for high voltage is satisfactory.

The above general remarks apply both to compensating cable (thermo-electric pyrometers) and copper cables.

When switches are used, e.g. in the case of a number of thermocouples operating with one measuring element, these should be of the double pole type with, preferably, uncorrodible metal contacts.

The most important items of maintenance are regular inspection of the condition of all joints and contacts, and regular accuracy checking, especially in the case of thermo-electric instruments. Replacement thermocouples should always be kept in stock.

Installation and maintenance of electrical measuring elements are on the same general lines as for other classes of industrial measuring instruments. They should be protected from vibration, dust and dirt, etc., pens should be kept filled with ink, and so on. The driving mechanism for null balance equipment will require routine attention and when using dry batteries with instruments of the potentiometric type, these must be replaced at intervals. Similar maintenance will be required for resistance thermometer equipment. The instrument maintenance routine is determined to a major degree by the individual make and type of equipment.

RADIATION PYROMETERS

Instruments of this type utilize the emission of radiant energy from the hot body for measuring its temperature. In general, the instrument makes no actual contact with the hot body, this method being used for temperatures that are higher than can be satisfactorily dealt with by a thermo-electric pyrometer, and for measuring the temperature of inaccessible bodies, e.g. the inside of a furnace or kiln.

Three kinds of pyrometer operating on this general principle are available, viz. (a) Total Radiation, (b) Optical and (c) Light-sensitive (photo-electric).

Total Radiation Pyrometers

These instruments measure the intensity of all the wavelengths of the radiation emitted from the hot body. These rays are focussed on to a temperature-detecting element by means of lenses or mirrors (Fig. 16). The detecting element is usually a thermocouple, though a resistance element or even a bi-metallic strip may be used. The thermocouple element is made of very fine wire and its cold junction may be contained in the radiation receiving unit but protected from radiation from the hot body. In these circumstances, both hot and cold junctions are very nearly equally affected by ambient temperature variations. Alternative means are available for obtaining cold junction temp-

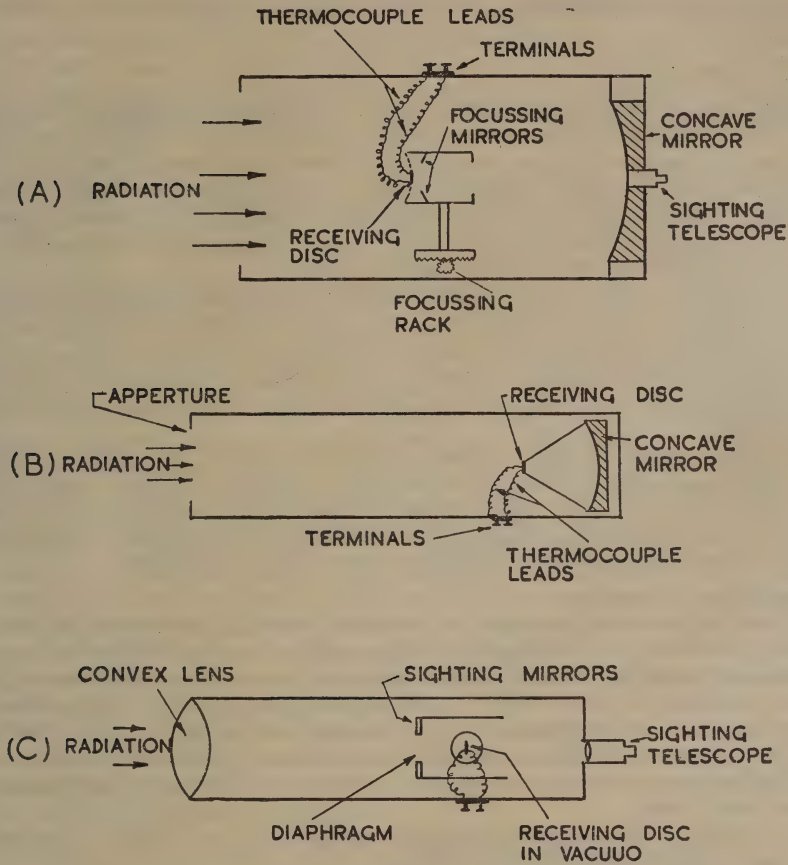


FIG. 16. Types of radiation pyrometer.

erature compensation. The remaining part of the equipment is identical with a thermo-electric pyrometer, i.e. the thermocouple is connected to the temperature measuring element by means of an electric cable. The temperature scale is not uniform (as in resistance thermometers and thermo-electric pyrometers) but opens out towards the upper end, because the radiant energy emitted from a body is approximately directly proportional to the fourth power of its Absolute temperature (See "Radiation", Chapter 9).

For accurate temperature measurement, the area of the hot body under observation must fill the field of "vision" of the radiation receiver, which, therefore, must be correctly sighted. There is, therefore, a definite relationship between the diameter of the hot body and its distance from the focussing lens or mirror. In addition, black-body conditions must be obtained as nearly as possible to ensure that all the radiation emitted from the body is solely due to its temperature. The nearest approach to ideal black-body conditions is the measurement of temperature in an enclosed furnace, the only aperture being the peephole through which the interior is viewed. Whatever the colour of the furnace and its contents, when cold, its interior will appear quite black. Therefore, when it is hot, the radiation emitted from the walls and material it contains will be solely due to the temperature. When ideal black-body

conditions are not obtained, a correction must be applied to the observed reading.

Optical Pyrometers

These are used for manual operation, i.e. for the spot readings of temperature. The operation consists of matching a standard source of light, e.g. from the filament of an electric lamp, with the light emitted from the hot body. The intensity of light from the standard source can be varied until the filament merges into the background formed by the hot body (*disappearing filament method*). The current flow through the lamp for this condition is measured, in terms of temperature, by an electrical instrument.

Alternatively, a grey wedge is interposed between the standard source of light and the hot body (Wedge Pyrometer). The position of the wedge at the matching point is a measure of the hot body temperature.

There is also the polarizing pyrometer, which polarizes the light from the two sources in planes at right angles, an adjustment being made to obtain a balance of brightness.

Generally a monochromatic screen is used in optical pyrometers so that matching is made on a particular wavelength, usually of red light, there being an accurately known relationship between temperature and intensity of radiation for each wavelength. As in the instance of the total radiation pyrometer, an effort should be made to work under black-body conditions.

Light-sensitive pyrometers

With this system, a light-sensitive element, usually a photo-electric cell, is used for measuring the intensity of light emitted by the hot body; the red and infra-red bands of the spectrum are generally used. The magnitude of the current through the cell (which must be energized by the e.m.f. from an external source), is determined by the intensity of radiation. The current, which is extremely small, is amplified electronically and fed either into a direct deflection indicator or recorder, or into a null balance instrument of conventional form.

The rectifier or barrier type cell generates its own e.m.f. which is sufficient to operate a sensitive measuring instrument.

The advantage of the light-sensitive method of measurement is that the response of the detecting element is practically instantaneous. It can, therefore, be used for measuring the temperature of rapidly moving objects.

As in the case of other radiation types of instrument, it obeys the Stefan Boltzman radiation law and the accuracy is affected by the departure from black-body conditions.

General characteristics of radiation pyrometers are given in Table 3.

TABLE 3.
CHARACTERISTICS OF RADIATION PYROMETERS.

<i>Type of Equipment</i>	<i>Application</i>	<i>Overall industrial temperature range</i>	<i>Distant reading</i>
Total radiation.	Radiating surfaces	500° C. upwards	Suitable
Optical	Radiating surfaces	700° C. upwards	Not suitable
Light sensitive	Radiating surfaces	700° C. upwards	Suitable

One of the most important points to note when installing and using radiation pyrometers is to ensure that the field of vision of the pyrometer is completely

filled by the hot body radiation. In some total radiation pyrometers no adjustment is provided, so there is a maximum "distance factor", i.e. relationship between maximum permissible distance from the sighting tube to the hot body, and the smallest dimension of the hot body. Other forms use focussing lenses. To facilitate the setting, a sighting hole is frequently provided at the back of the tube.

The tube must be designed for the particular service under consideration. For example, when measuring the temperature in chambers under a pressure or suction, e.g. a steel furnace, the front end of the tube may be protected by a mica window, air being blown over it to keep it free from dust and dirt. Any protection calling for the interposing of a window or similar device between the sighting tube and the source of radiation calls for special calibration of the instrument by the manufacturer. It is necessary to select a focusing point that will not be influenced by direct or reflected glare from flames. Of course, it is quite impossible to measure the temperature of a body through intervening flames. When it is undesirable to have an open sighting hole in a furnace, kiln, etc., a refractory tube with a closed end can be fitted into the furnace wall and the radiation pyrometer focussed on to the inner end of the tube. This method generally results in a lower temperature reading. In certain cases, air-cooled or water-cooled sighting tubes are necessary. Attention is drawn to errors caused by intervening gases between the source of radiation and the pyrometer; these, notably CO_2 and water vapour, may be invisible. Mention has already been made of the effect of departing from the ideal black-body conditions; when such a departure is suspected, the advice of the instrument manufacturer should be sought.

The most important item of routine maintenance is to keep glass windows, lenses and mirrors scrupulously clean.

For permanently installed instruments, e.g. total radiation pyrometers, cable runs and insulation requirements follow the same lines as for electrical temperature measuring instruments, as does the installation and maintenance of the electrical measuring element.

SOME PRACTICAL ASPECTS OF TEMPERATURE MEASUREMENT

The art of accurate temperature measurement lies in the correct selection of the point of measurement and ensuring that the temperature-sensitive element is actually subject to the temperature to be measured, and is not influenced by extraneous factors. The following notes describe the salient factors to be observed in temperature measurement.

When temperatures of liquids are being measured, it is essential that the liquid be in an agitated condition to attain homogeneity and eliminate temperature gradients. The sheath or pocket of the temperature-sensitive element should be long enough to prevent conduction of heat or cold from the surrounding surface—the length immersed should be 10 to 20 times the diameter. It is desirable to fill any air space between a temperature-sensitive bulb and its pocket with a good heat conductor, e.g. oil if circumstances permit.

When the temperature in a small pipe is to be measured, the temperature-sensitive element should be inserted into a right-angle bend so as to obtain full immersion.

Build-up of foreign matter on the temperature-sensitive element will cause a serious time lag with consequent errors in reading. Cleaning at regular intervals may, therefore, be necessary.

When measuring the temperature of a gas, in addition to ensuring that the gas is in an agitated state at the point of measurement it must be remembered that the temperature-sensitive element may be affected by radiation from hot or (more usually) cold surfaces within its area of "vision"; reference has already

been made to the suction pyrometer. For "still" gas temperature measurement capillary type bulbs are available long enough to smooth out temperature gradients and having a large heat transfer area in relation to their mass.

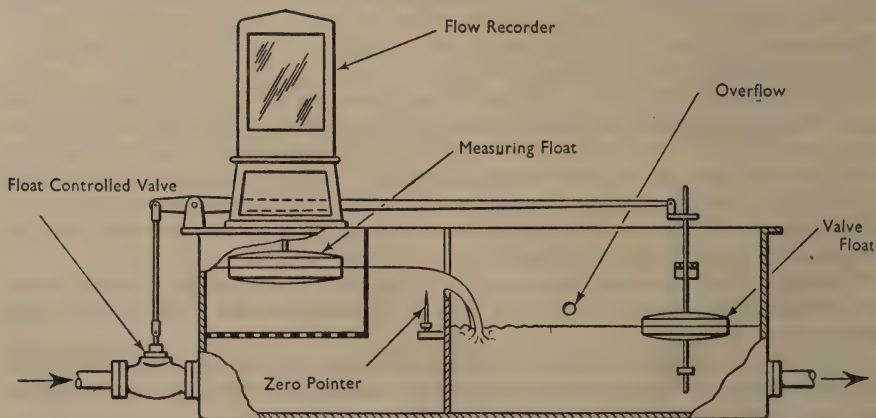
Surface temperature measurement presents its own particular difficulties. On smooth machined surfaces good reproducibility is obtained; air spaces between the temperature-sensitive element and the surfaces of cast metals and refractories may result in unreliable readings. When using a mercury thermometer, one with a small narrow bulb is to be preferred, the bulb being pressed to the surface with a thin plate of metal and not a non-conductor of heat. Air spaces may be filled with a paste of copper or aluminium powder in oil. For surface temperature measurement, various forms of thermocouple are available. These are of thin, flexible strip or similar construction and tend to conform to the shape of the surface on to which they are pressed. Thermocouples embedded in the surface may also be used.

FLOW MEASUREMENT

A wide range of equipment is available for metering the flow of fluids (liquids and gases). In industrial practice, fluid flows are nearly all confined to closed conduits, one important exception being the measurement of the flow of feed water on the suction side of a boiler feed pump. The equipment for this purpose falls within the category of (A) Open Channel Flow Metering. For closed conduits, the classes of meters available are (B) Mechanical, (c) Differential Pressure, (D) Shunt and (E) Variable Aperture.

(A) OPEN CHANNEL METERS

The only form of equipment of this type considered here is the *weir meter*. This consists of a tank with a transverse partition containing either a 'V' notch or a rectangular weir. The water to be metered flows into one end of the tank, through the notch, and is discharged from the other end of the tank. The depth of flow over the invert of the 'V' or cill of the rectangular notch is a measure of the rate of flow. The notch forms the detecting element; the measuring element may be a hook gauge or a surface pointer but is usually of the float-operated form. The float is housed in a compartment formed in the weir tank and in communication with it, so that the float rises and falls with the depth of flow over the weir (Fig. 17). The float movement is transmitted to the



Sectional Elevation

FIG. 17. Notch tank.

registering portion of the equipment by a cord, rack or similar mechanical device and recorded, in terms of rate of flow, on a paper chart. The flow rate may also be indicated on a scale and integrated. Since the flow/depth relationship is not linear, some device for obtaining a linear relationship is required for integration. This may take the form of a cam with a shaped profile through which both recorder and indicator can be operated so as to obtain an equally spaced scale. The flow registration can be transmitted electrically to a distant point.

Before any readings are taken, the level of the tank and weir should be confirmed by a spirit level and the zero setting of the indicator checked. A zero pointer may be permanently fixed to the tank with its point set exactly level with the bottom of the notch or weir. On account of the confusion that can be caused by surface tension effects, zero setting should never be verified by reference to the level reached by the water at the moment when the flow over the notch just ceases.

The water level on the downstream side of the weir plate must always be not less than from 1 inch to 3 inches below the weir to ensure a free overfall. Some form of flow control is also required to match the supply of water with the demand by the feed pump. This is achieved by fitting an inlet valve operated by a float located in the compartment on the downstream side of the weir; as the level here falls, the inlet valve is opened, and *vice versa*. (For fuller details see B.S. 599, §§ 14, 17.)

The approach flow to the weir must be steady and free from swirl and turbulence. To attain this steady approach it is usually necessary to fit baffle plates in the tank between the inlet and the notch plate. More than one plate can be used if the water entry is exceptionally turbulent.

The flow formulae, from B.S. 599², are:

- (a) 90° *V*-notches for measurement of discharge of
900–90,000 gal./hr. $G = 117.2 h$.

This is derived from the general equation

$$(\text{Barnes' Formula}) \quad G = 116.3 h^{2.48} \times \tan \frac{\theta}{2} \left(\frac{1}{2} \sin \frac{\theta}{2} \right)^{0.00703}$$

- (b) *Rectangular weirs* of any length from 12 in. upwards where $\frac{l}{h}$ is greater than 2, and for measurement of discharges

$$\text{exceeding } 15,000 \text{ gal./hr., } G = 147.9 (l - 0.1 h) h^{1.5}$$

In these formulae

G = gallons per hour,

h = head over invert of 'V' notch or cill of weir, in inches,

θ = angle of the 'V' notch,

l = length of the cill, in inches.

When applied to weir tanks, these and other formulae should be treated with caution, since they apply only when the design is in accordance with certain conditions rarely obtainable in a weir tank (because of limited space).

When practicable, feed water measurement by a weir has many advantages. One of the most important is that the accuracy of registration is unaffected by pulsations caused by reciprocating feed pumps and by the "on-off" action of certain forms of feed water regulators. Theoretical considerations show that the weir meter measures the actual volume passed irrespective of its density. Since the weight of flow is required, the measuring unit must be calibrated to read correct for a stated temperature. Due to the change in immersion level of the float with change in temperature, when calibrated in weight units there is a tendency towards automatic temperature compensation.

The most important item of installation and maintenance is to make sure, by periodical checks, that the equipment is correctly set to zero and kept so, otherwise, serious errors in registration are inevitable, especially during sustained periods of low flow. Planimetering the chart and comparing the result with the counter reading over the same period is no check on whether there is a discrepancy between the position of the float and the corresponding position of the registering mechanism.

(B) MECHANICAL METERS

The characteristics of mechanical meters are such that they are limited to measuring the flow of liquids (hot or cold water, oil and petroleum products), give a counter (integrated) reading of only the total flow passed and always register the actual volume passed irrespective of the density of the liquid. These can be calibrated to register in weight units at a specified density. The detecting and measuring elements form one unit, the former either consisting of a fan, helix or similar element (*inferential meters*) or a moving member in the form of a piston (*displacement meters*). The measuring unit consists of either a circular or a straight reading counter driven through a train of gears by the detecting element. The movement of the detecting element is transmitted to the counter *via* a pressure-tight gland; alternatively, magnetic transmission may be used.

Inferential meters

These measure velocity of flow rather than quantity, the volume passed being the product of the velocity and the cross-sectional area of the working chamber, which is constant. A fan on to which the liquid impinges through one

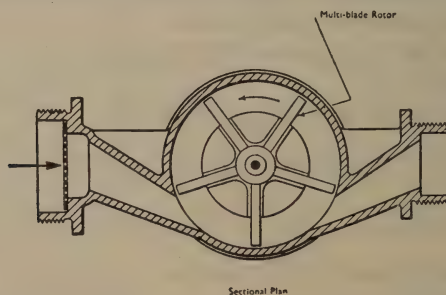


FIG. 18. Inferential meter. Single jet fan type.

or more nozzles, is usually used in the smaller ranges of meter (Fig. 18), larger meters utilizing a rotor in the form of a helix which may be mounted on a horizontal (Fig. 19), or vertical axis (Fig. 20). These meters range in size from $\frac{1}{2}$ inch up to 12 inches and over, a range that covers all industrial requirements. The maximum flow in relation to size is an arbitrary figure—it is usual to specify a maximum flow for continuous working that will not cause excessive head loss (usually about 12 inches w.g.) and a low rate of wear so as to give a long working life. Heavy overloads will be accurately metered. The accuracy guarantee is usually ± 2 per cent. over the whole working range, which is of the order of 1 in 20. Typical flows (water) are a *minimum* of 8 g.p.h. for a $\frac{1}{2}$ inch meter and 4,000 g.p.h. for a 10 inch meter.

Displacement meters

In these the volume registered is determined by the actual displacement of the piston during each of its cycles. The most widely used form of piston has a semi-rotary movement. It is used in meter sizes ranging from $\frac{1}{2}$ inch to

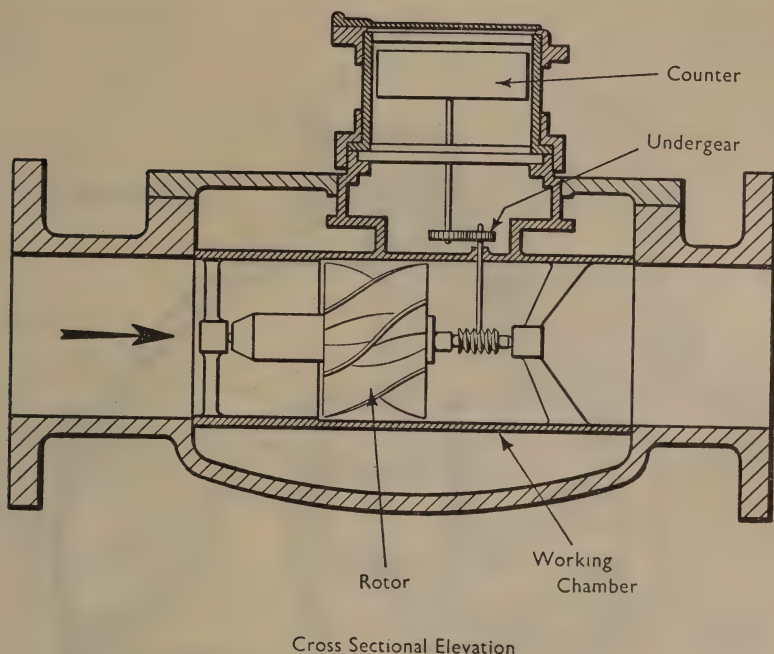


FIG. 19. Helix type inferential meter. Horizontal axis.

6 inches (Fig. 21). There are, however, other forms, notably the duplex piston meter, in which both the pistons are cylindrical and the liquid, in flowing through the meter, imparts to them a combined oscillating and semi-rotary movement.

As in the case of inferential meters, the maximum flow that can be dealt with by each size is based on practical experience. With regard to range, due to the principle of operation, there is less "slip" in these meters so that a displacement meter can measure down to a lower flow than an inferential meter of the same nominal capacity and with the same degree of accuracy (± 2 per cent.); the flow range is of the order of 1 to 40. For example, a typical $\frac{1}{2}$ inch meter would register down to 4 g.p.h. of water. The minimum flow that can be registered is greater the lower the viscosity.

Inferential meters are generally used for water metering in connection with supply services, and displacement meters for oil, e.g. to oil-fired boilers, petroleum products as well as water measurement. Specially designed reciprocating piston meters of the type referred to can be specially calibrated *in situ* using the actual liquid to be metered, to give an accuracy of well below 1 per cent. over a limited flow range.

Both inferential and displacement meters are used for metering hot boiler feed, but with both forms trouble is possible with reciprocating feed pumps. The pulsations may cause an inferential meter to read fast; those of the displacement meters may result in a broken piston. From the metering point of view, the air vessel usually encountered on a reciprocating feed pump is generally useless.

Particularly in the instances of displacement meters, various types of counter dials are available, such as large vertical ones for oil and petrol measurement, together with various re-set and pre-set automatic shut-off devices.

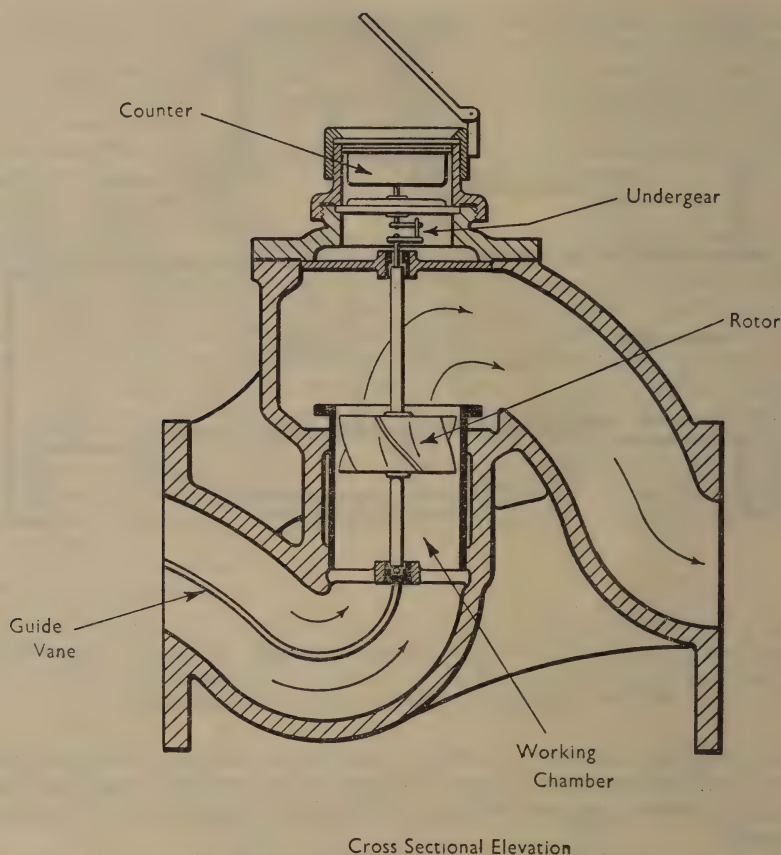


FIG. 20. Helix type inferential meter. Vertical axis.

In all mechanical meters the materials of construction of the parts in contact with the metered liquid are determined by the nature of the liquid. Various non-ferrous alloys are used for water, plastics, aluminium, etc. for petrol, and so on.

As a general rule, inferential meters are affected to a varying degree by disturbed hydraulic conditions on the upstream side. The manufacturers' installation instructions must, therefore, be carefully followed. On the other hand, displacement meters are not so affected and some designs can be mounted in any position, e.g. in a vertical or inclined pipe; here again the manufacturers' instructions should be followed.

It is important that the meter be mounted in a position where it will be subjected to a sufficiently high back pressure to keep it full of the metered liquid. In the case of hot liquids, e.g. boiler feed, the pressure should be sufficient to prevent any tendency towards boiling in the meter. Air release valves may be required when metering petrol.

When first putting into operation, on installing or after an overhaul, the control valve should be opened slowly to prevent a rush of air from damaging the meter. The only permanent protection required is against risk of damage from freezing.

The only maintenance required by metering equipment of this type is periodical inspection of the working parts and cleaning of working chamber, strainer,

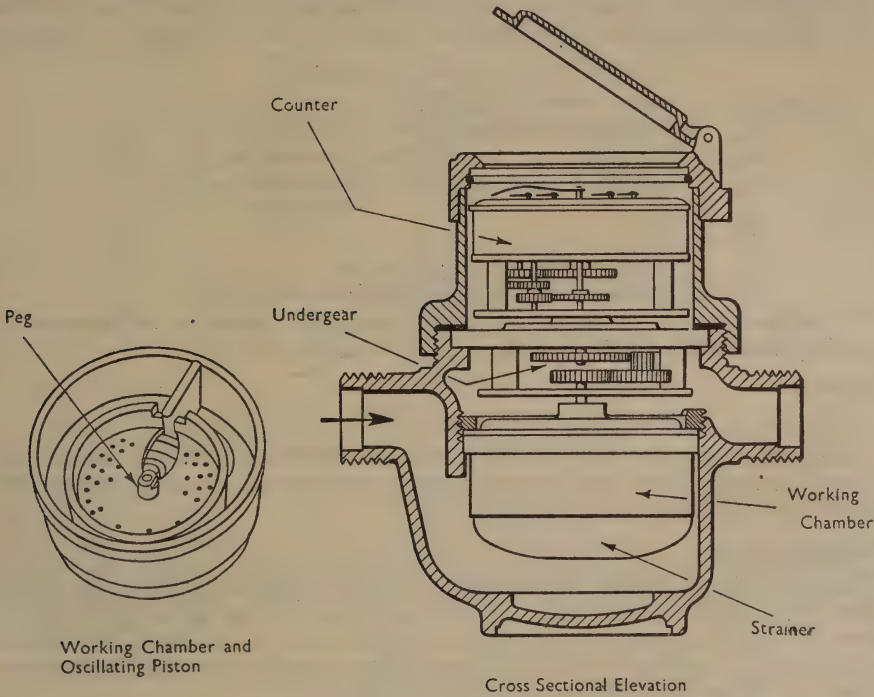


FIG. 21. Displacement meter. Semi-rotary circular piston type.

etc. It has been mentioned that mechanical meters always register correctly the actual volume passed. If calibrated in weight units for a liquid of density W_m and the actual density (on account, say, of a temperature change) is W_a , the meter reading must be multiplied by the factor W_a/W_m .

(C) DIFFERENTIAL PRESSURE METERS

Flow meters of the differential pressure form have the widest application; they are used for measuring the flow of most fluids, notably water, steam, air and gas. The equipment consists of a differential pressure generating device (the detecting element) and an instrument for measuring the differential pressure (the measuring element). The measuring element translates the differential pressure into terms of rate of flow and can indicate the instantaneous flow rate on a dial, record the flow variations on a paper chart, and integrate the flow on a counter. Two small-bore pipes are used to transmit the differential pressure from the detecting element to the measuring element. The measuring element can be located at a distance from the measuring element, and mounted either on a pedestal, a wall or a panel, in accordance with requirements.

The detecting elements most widely used are:—(a) the orifice plate, (b) the Venturi tube, (c) the Dall tube and (d) the Pitot tube.

The function of the detecting element is to form a local restriction in the cross sectional area of flow, this contraction resulting in an increase in velocity of flow of the metered fluid which is accompanied by a reduction in pressure at this point. The difference in pressure between a point upstream of the restriction and that obtained at or slightly downstream of the restriction is a measure of the rate of flow.

The general flow formula for all differential pressure generating devices, with the exception of the Pitot tube, is

$$Q = 0.127 C_d a_2 \sqrt{h/W} \div \sqrt{1-m^2},$$

where Q = rate of flow; cu.ft./sec.

C_d = discharge coefficient

a_1 = cross-sectional area of the upstream; sq. in.

a_2 = cross-sectional area of the contraction; sq. in.

$m = \frac{a_2}{a_1}$

h = differential pressure; inches w.g.

W = density of the metered fluid; lb./cu.ft.

To obtain the flow in weight units, i.e. pounds per second, it is necessary to multiply both sides of the equation by the density, W .

Hence,

$$QW = P = 0.127 C_d a_2 \sqrt{hW} \div \sqrt{1-m^2} \text{ lb./sec.}$$

The relationship between rate of flow and differential pressure can be expressed in many ways, but for occasional calculations, to avoid errors, the above basic formulae are to be preferred.

The orifice plate

This, the simplest form of detecting element, consists of a thin flat metal plate e.g. of stainless steel with, usually, a central circular hole. For metering flows through a circular pipe—and this covers most applications—the orifice plate would be inserted between adjacent flanges, the plate being made in the form of a disc to fit within the bolt circle, (Fig. 22.)

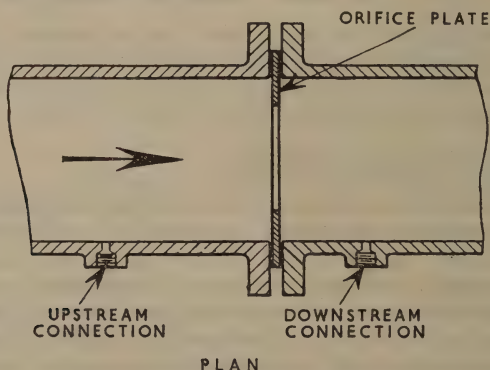


FIG. 22. Orifice plate assembly.

There are alternative positions for measuring the two pressures; those widely used are at a distance of (a) one pipe diameter upstream of the plate and (b) half a pipe diameter downstream. Alternatively, especially where a small pipe is involved, the two radial tappings may be made by drilling through the flanges, the pressure measurements being made in the plane of the plate. The disadvantage of these forms of tappings is that bosses have usually to be welded into the pipe at the appropriate positions and drilled. Furthermore, the differential-pressure/flow relationship will be affected if the actual pipe diameter differs from the nominal diameter. In such cases the pipe bore must be measured and the equipment calibrated accordingly. These difficulties are eliminated by using a carrier orifice plate, i.e. a plate held in a carrier

incorporating the two pressure tapings—in the plane of the plate. This assembly is inserted into the pipeline between adjacent flanges (Fig. 23).

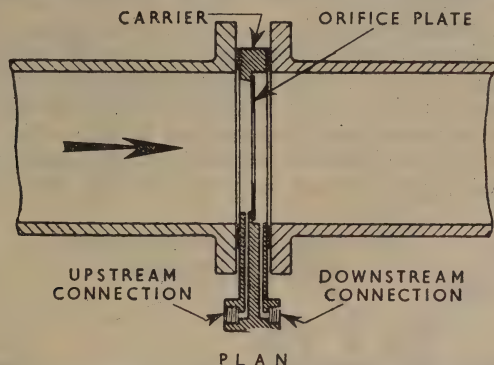


FIG. 23. Orifice plate with carrier ring for pressure tapings.

The average value of the discharge coefficient, C_d , for orifice plates is approximately 0.62.³

For metering heavy oils, of viscosity such that the differential-pressure/rate-of-flow relationship is modified, special thick orifice plates with a shaped bore are available which, within known limits, automatically compensate for viscous effects (Fig. 24.)

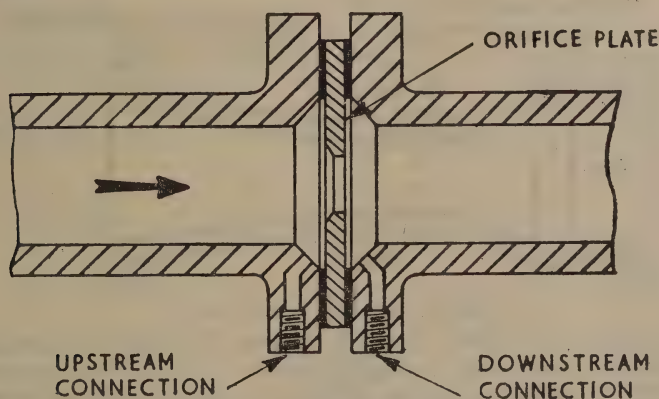


FIG. 24. Assembly of orifice plate for measuring the flow of viscous liquids.

The irrecoverable pressure loss through an orifice plate is of the order of 60 per cent. (and upwards) of the differential pressure generated.³ Since the differential pressure generated for medium and high pressure work is of the order of 2 pound per square inch or so at the maximum flow, this loss is not important. In fact, the orifice plate is almost universally used for metering steam where a continuous indication or recording of the flow is required and perhaps a counter record. For low pressure work, and where large volumes of fluid are involved, additional head loss may result in a significant increase in the cost of pumping the fluid through the pipeline. In such instances the Venturi tube and the more recent Dall tube are used.

The Venturi tube

The basic construction of the Venturi tube is two truncated cones, the smaller diameters of which are connected by a short length of cylindrical pipe.

The larger diameters are equal to the diameter of the pipeline into which the assembly is fitted. The short parallel pipe constitutes the "throat" and the lower pressure is measured here. The higher pressure is measured just upstream of the commencement of the upstream contraction—a short length of parallel pipe here forms an integral part of the Venturi tube.

The downstream expansion cone is for pressure recovery purposes; the irrecoverable pressure is of the order of 15 per cent. of the differential pressure generated, the exact value being determined by the ratio of the throat to upstream diameter and the included angle of the expansion cone.

Design details of Venturi tubes vary widely (Fig. 25). There is usually,

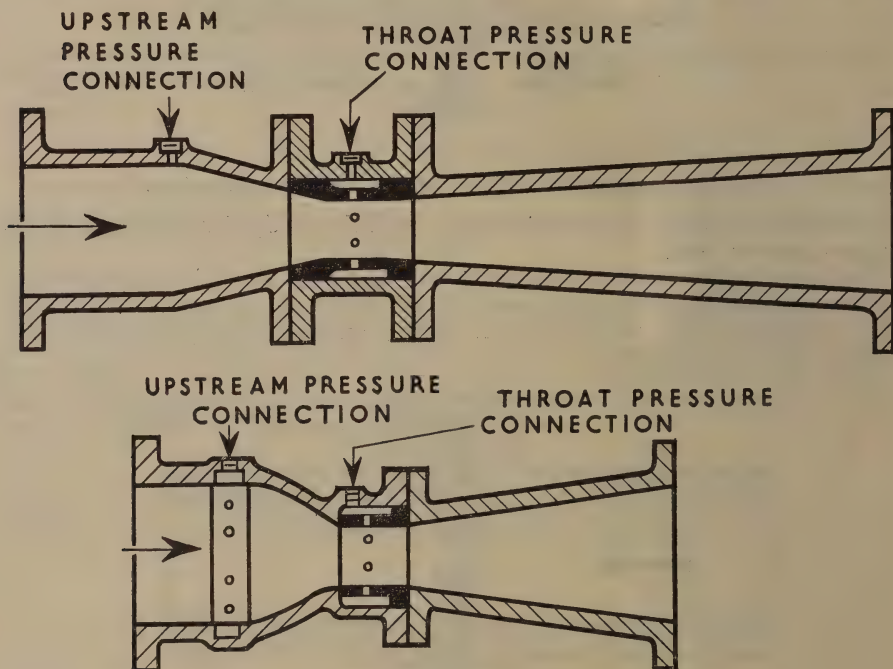


FIG. 25. Typical Venturi tubes.

around the throat, a covered chamber ("piezometer ring") in communication with the interior of the tube through a number of holes, one pressure tapping being made in the *annular chamber*. A similar construction may be used at the upstream pressure measuring point. The throat is made of a corrosion-resistant material, e.g. gun-metal, machined to the required contour and inserted into a casing, generally of cast iron.

The discharge coefficient, C_d , of Venturi tubes lies between 0.96 and 0.98, depending on the design.³

The Dall tube

The basic principle of operation of the Dall tube is the same as that of the Venturi tube; the difference lies in the fact that the upstream and downstream cones have both a very much larger included angle and, instead of a parallel section to form the throat, there is a narrow circumferential slot in which the throat pressure is measured (Fig. 26). The effect of the slot type of throat is to cause an additional reduction in pressure at this point so that a larger differential pressure is obtained without any increase in irrecoverable pressure loss; an average value for this loss is 6 per cent. of the differential

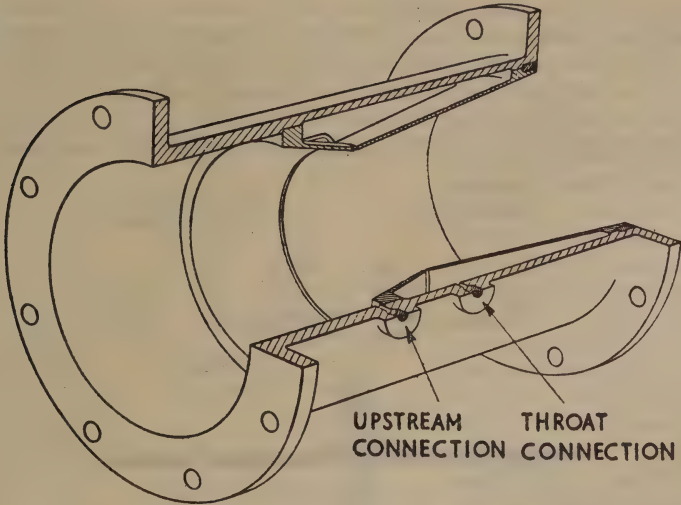


FIG. 26. A Dall tube in part section.

pressure generated. At the same time, the overall length, and consequently the cost, of this tube is less than that of the conventional form of Venturi tube.

The Pitot tube

This is, essentially a velocity measuring device. It consists of a tube, which may be of stainless steel, of small bore with a sealed end, near which an orifice is drilled in the wall of the tube. This assembly, known as the *Single Tip Pitot tube*, is inserted, through a pressure-tight gland, into the pipeline with the orifice facing upstream in the direction of flow of the fluid (Fig. 27). The

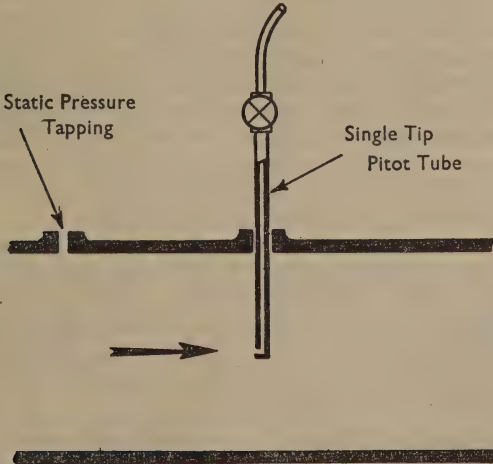


FIG. 27. Single-tip Pitot tube assembly.

pressure within the tube will then be equal to the static pressure *plus* the “velocity head” i.e. the pressure due to the fluid being brought to rest as it enters the tube. By making a static pressure connection in the wall of the pipeline, and measuring the difference between the two pressures, the velocity of flow at the Pitot tube orifice can be calculated according to the Equation:

$$V = \sqrt{2gH}$$

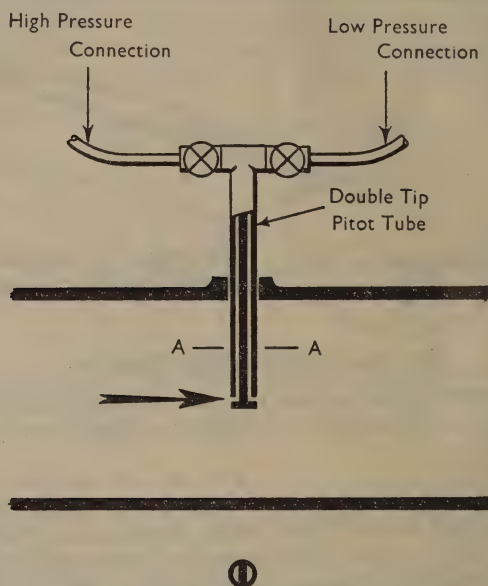
where V = velocity: ft./sec.

g = acceleration due to gravity: (32.2 ft./sec.²),

H = differential pressure: in terms of feet w.g.

The "discharge coefficient" of the device is unity.

In an alternative design, referred to as the *double tip Pitot tube* (see Fig. 28),



Section A A

FIG. 28. Double-tip Pitot tube assembly.

the tube is divided into two longitudinal compartments, each of D-shaped cross-section, by a longitudinal partition. Each compartment has an orifice near the sealed end, these openings being diametrically opposite each other. When the unit is inserted into the pipeline with one orifice pointing upstream and the other downstream, the difference between the pressures in the two compartments is equal to the impact head *plus* the suction head. For any given velocity, the differential head generated by a double tip Pitot tube is thus greater than that generated by a single tip Pitot tube.

For accurate flow measurement with a Pitot tube the pipeline should be traversed, a single tip tube being used for this purpose. By this means the relationship between mean velocity to velocity at the point where the orifice is located can be ascertained. For approximate work with a single tip tube and with its orifice in the centre of a circular pipeline, $V_m = 0.8\sqrt{2gH}$, where V_m is the mean velocity in feet per second. When a double tip Pitot tube is used, the formula becomes $V_m = 0.68\sqrt{2gH}$.

The Pitot tube is generally limited to experimental work and for investigation purposes; it can be used to measure the velocity of all fluids. One commercial steam flow meter utilizes this form of detecting element. The equipment suffers from the disadvantage that it is not possible to alter the velocity/differential head relationship. On the other hand, it causes no pressure loss.

Measuring Elements of Differential Pressure Meters

The function to be performed by these instruments is similar to that performed by a pressure measuring instrument so, in principle, the design is the

same; by opening one side of a differential pressure measuring instrument to the atmosphere, it can measure pressure. Here also, both "wet" and "dry" types are available.

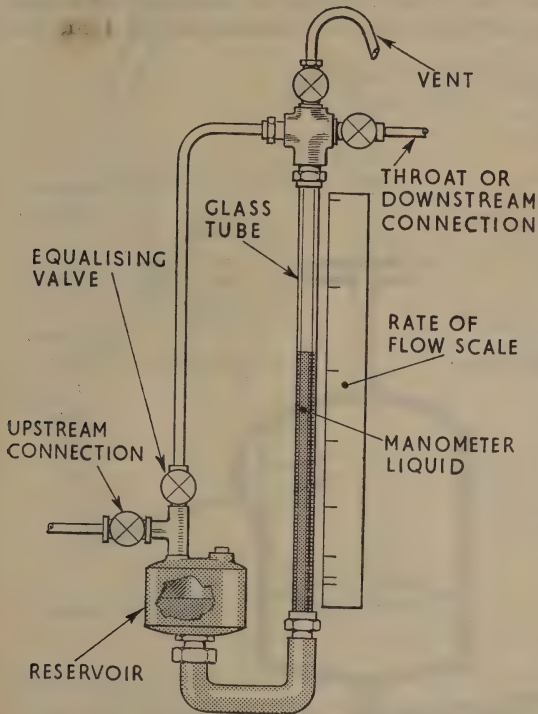


FIG. 29. U-tube manometer. Single tube type.

which would be ample for most applications. An oil-filled curved tube manometer, on the other hand, could be arranged to give full scale deflection for a differential head of an inch or two w.g. The manometer scale could be graduated in terms of differential head or rate of flow.

"Wet" types

The simplest of these is the glass tube manometer, described under **PRESSURE MEASUREMENT**, above. One limb is connected, through small bore pipe, to the upstream tapping in the detecting element, and the other limb to the lower pressure tapping (Fig. 29). For liquid measurement, and also for gas measurement under high differential pressures, mercury is used as the manometer liquid. Oil is used for low pressure gas measurement. For low differential pressure, the manometer tube may be inclined (Fig. 30) or curved. The highest differential head which can be measured by a manometer is determined by practical convenience; a mercury manometer (s.g. of mercury = 13.56) with a glass tube 30 inches long could deal with a differential head of over 350 inches w.g.

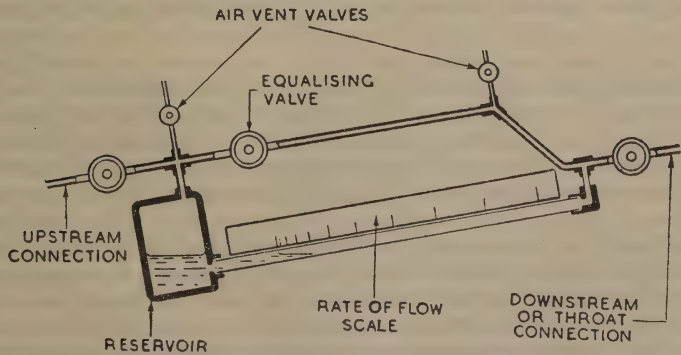


FIG. 30. Inclined tube manometer.

To obtain a record of flow variations on a paper chart and also, if required, an integration, a different form of instrument is required. For large differential heads, associated with high working pressures, a metal

U-tube containing mercury is used. One of the two chambers contains a metal float resting on the mercury, so that it follows changes in mercury level. The float movement is transmitted to the outside of the assembly through a bell crank or equivalent mechanism which rotates a spindle housed in a pressure tight gland (Fig. 31). In another design, magnetic transmission is used. The

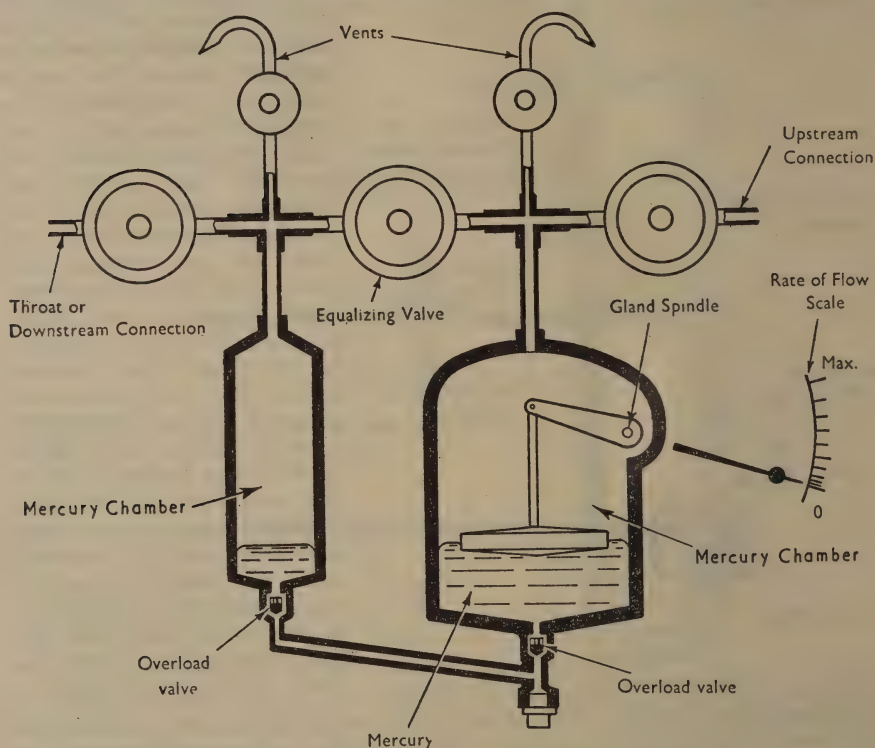


FIG. 31. Mercury U-tube registering instrument.

output so obtained is used to drive the registering mechanism.

Examination of the flow formula already given shows that there is a square root relationship between rate of flow and differential head. Consequently there is a progressive contraction of the rate of flow scale towards zero. To obtain an equally spaced scale, one of the mercury chambers may be specially shaped. Alternatively, instead of using a float, a shaped bell or displacer may be used. To obtain an equally-spaced movement for integration purposes when a shaped chamber or displacer is not used, some link or cam mechanism (Fig. 32), must be introduced between the gland spindle and the integrating unit.

For differential heads less than about 10 inches w.g., associated with low pressure air and gas measurement, the ring balance form of instrument is widely used. The moving element consists of a hollow ring mounted on a knife edge. The ring is partly filled with oil, and is fitted with a partition at the top, so that two compartments are formed, to one of which the higher pressure is applied, the lower pressure being applied to the other compartment (Fig. 33). Short lengths of flexible pipe are used to transmit the two pressures to the ring. Under the influence of the differential pressure, the ring turns about the knife edge, its turning moment being counterbalanced by a weight. The angle of deflection of the ring is related to the differential pressure applied, and is

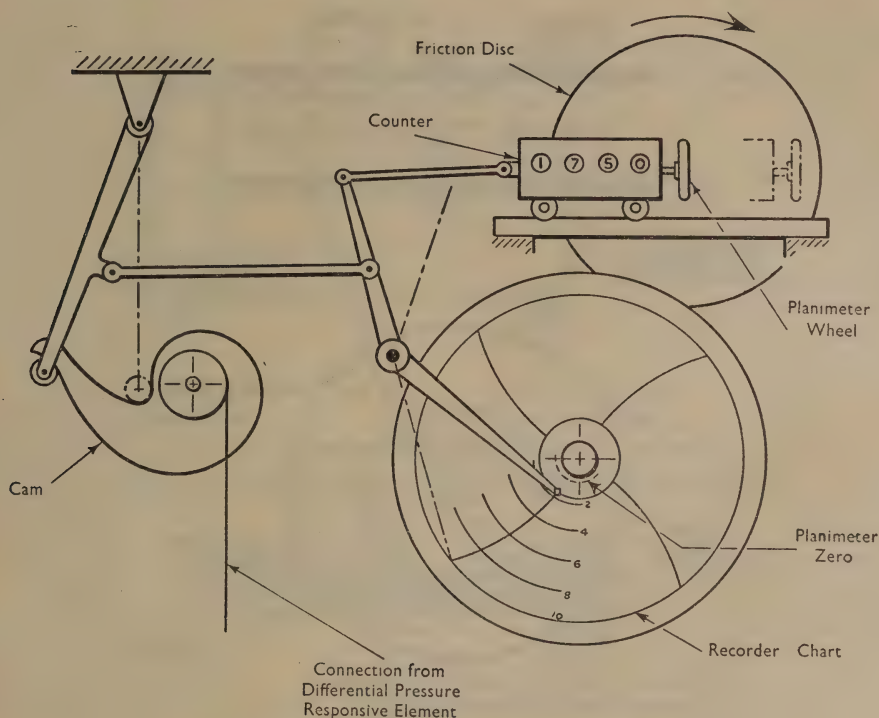


FIG. 32. Continuous integrating mechanism.

registered in terms of rate of flow. Instruments of this description can give full scale deflection for a differential head less than 1 inch w.g.

In another design of low pressure instrument, the moving element consists of a bell suspended by a spring or springs in a bath of mercury or oil, the whole assembly being sealed. The higher pressure is applied to the outside of the bell and the lower pressure to the underside of the bell (Fig. 34). Under the influence of the differential pressure the bell is displaced, the amount of the displacement being determined by the strength of the suspension spring. Through a pressure-tight gland, the bell movement is transmitted to the registering mechanism.

"Dry" types

In these the liquid seal is replaced by a diaphragm or bellows unit. For example, by modifying the design of a draught gauge it can be used as an instrument for measuring low differential pressures.

Bellows type instruments are available for maximum heads of about 10 inches w.g. upwards and for the highest working pressures encountered in practice.

In modern designs of bellows type instruments, the conventional spring control is replaced by a "torque tube", the bellows unit being connected to this through flexible metal strips. The torque tube assembly consists of a spindle contained within a tube. The inner end of the spindle is welded to the tube, the outer end of the tube being welded to a housing attached to the meter body. The metal strips are clamped to the inner end of the tube (Figs. 35 and 36). When the bellows unit is subjected to a differential pressure, its change in length is controlled by the torque tube, a twist being imposed on this. The amount of twist, which is proportional to the differential pressure, is imparted to the

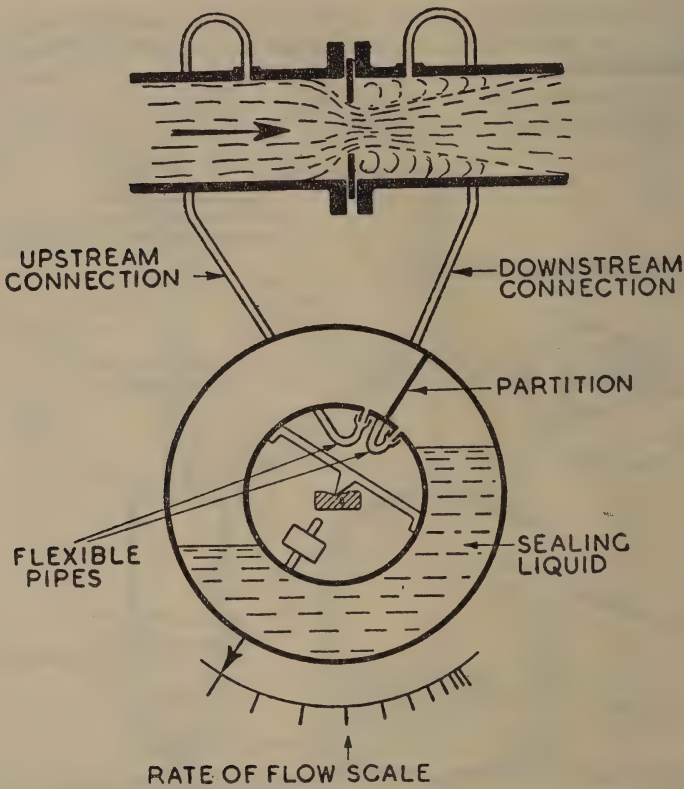


FIG. 33. Ring balance differential pressure flow meter.

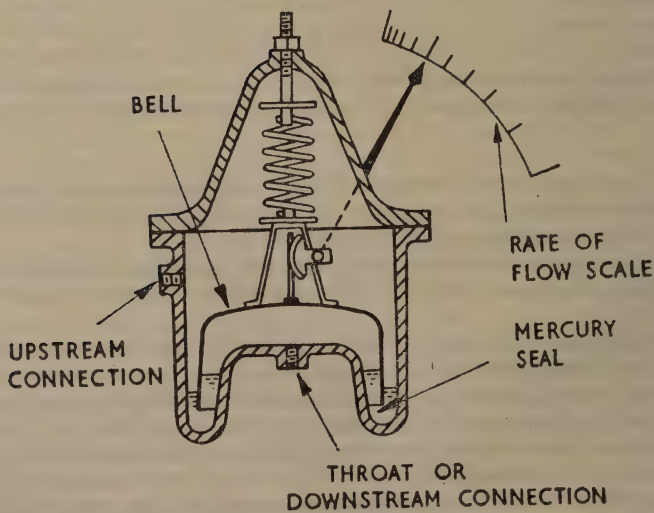


FIG. 34. Bell type differential pressure flow meter.

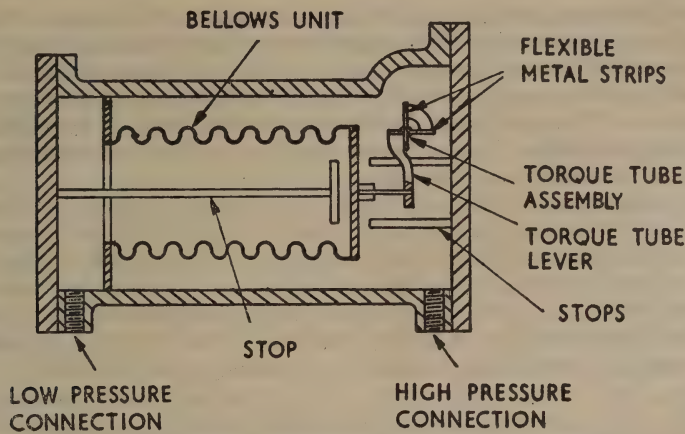


FIG. 35. Bellows type differential pressure flow meter.

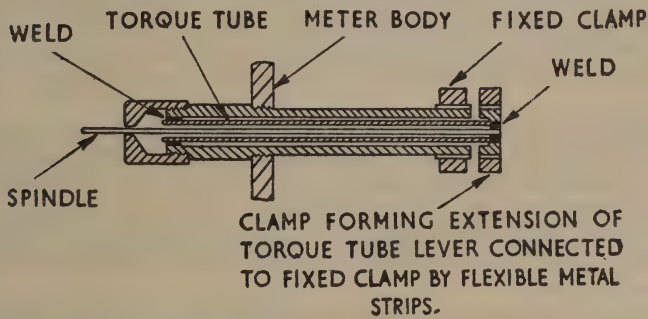


FIG. 36. Torque tube assembly, for flow meter illustrated in FIG. 35.

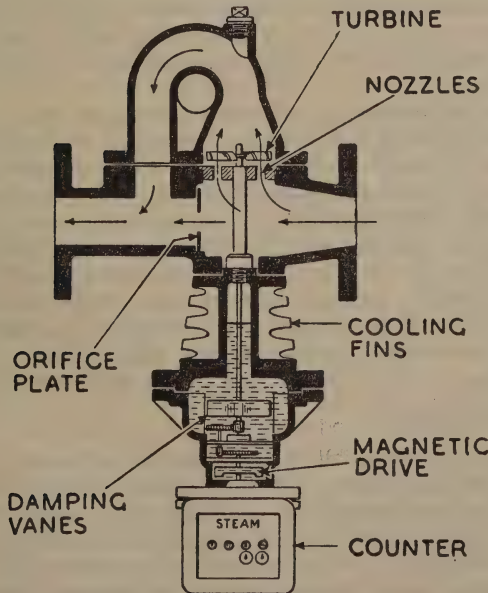


FIG. 37. Shunt type flow meter.

spindle and this operates the registering mechanism. The range of the instrument is altered by replacing the torque tube by one of different wall thickness.

Although a differential pressure meter will not be damaged by an overload it will not register one. Also, on account of the square root flow law, the flow range is limited; the usual range is from maximum down to one-eighth or one-tenth of the maximum. The maximum flow to be metered should, therefore be estimated as accurately as possible.

These meters also register correctly for only one density of the metered fluid; automatic correction for pressure and temperature variations is technically possible but costly. Average conditions of temperature, pressure, etc., must, therefore, be specified if these are likely to vary. In practice, any metering errors due to this cause tends to cancel each other out; if not, a correction factor must be applied to the meter reading. When the meter is calibrated in weight units, e.g. pounds per minute, the factor equals $\sqrt{W_a/W_m}$

where W_m = the density of the fluid for which the meter is calibrated
and W_a = the actual density of the fluid being metered.

When calibrated in volume units, e.g. gal./hr., the factor equals $\sqrt{W_m/W_a}$. Some meters are calibrated to register the volume of flow in "reduced units", e.g. in the case of a gas its volume reduced to standard pressure and temperature. The same correction factor is used as for a meter calibrated in weight units.

Unsatisfactory metering is often due to failure to appreciate these points.

Differential pressure generating devices are adversely affected by disturbed hydraulic conditions in their vicinity. Consequently, they should be installed in a straight length of pipe and all flow control should be done on the downstream side. The length of straight pipe required is determined by individual circumstances. The calibration of the equipment is not affected if the pipeline is vertical or inclined.

Particular care is required in laying the pressure transmitting pipes between the detecting and measuring elements. In the case of liquid meters, they must be laid in such a manner that air locks are not formed. In the case of gas metering, water locks must not form. For liquid metering the pressure tappings should be in the side of the detecting element, while for gas metering they should be in the top.

In the case of steam metering, the pressure-transmitting pipes and measuring element must be kept full of water, for which reason cooling chambers, in which steam will condense, are mounted next to the pressure tappings.

The measuring unit must not be fitted above the hydraulic gradient, otherwise there is a risk of air leaking into the system and causing a metering error.

Important items of maintenance are: flushing the installation at regular intervals to discharge any trapped air (liquid metering), and checking the zero readings by equalizing the pressure on both sides of the instrument. All these instruments are provided with vent valves and an equalizing valve. When flushing a steam meter, the equalizing valve *must* be kept closed, otherwise the measuring element will by-pass steam and it will be seriously damaged.

(D) SHUNT TYPE METERS

These combine the principle of the inferential mechanical meter with that of the differential pressure meter. The meter body, inserted into the pipeline, contains an orifice plate which causes a certain percentage of the fluid passing through the meter to be shunted round a by-pass formed in the meter cover. In flowing round the by-pass, the fluid is directed by nozzles on to the blades of a small turbine mounted on a vertical spindle projecting downwards through the body into a compartment filled with water. The speed of rotation of the

turbine is proportional to the total rate of flow of fluid. The spindle is fitted with vanes on which the water has a damping effect, so reducing the speed of rotation. The lower extremity of the spindle carries a magnet, a follower magnet in a compartment on the underside of the meter body transmitting the spindle rotation, through a train of gears, to a counter, (Fig. 37).

These meters, of which only a counter record type is available, are suitable for measuring the flow of air, gas, steam and water. Since they are not very susceptible to pulsating flow, they are widely used for boiler feed water measurement, when the feed pump is of the reciprocating pattern. They are made in sizes ranging from 2 inches to 4 inches, and a feature is that the nominal maximum flow can readily be altered by changing the orifice plate. They have the same characteristic as mechanical meters in that they will accurately meter and not be damaged by, heavy overloads of short duration. The flow range, over which an accuracy of ± 2 per cent. is guaranteed, is from maximum down to about one-seventh of maximum.

As in the case of differential pressure meters, the accuracy of registration of shunt meters is affected by changes in density of the metered fluid. The same correction factors are used as for differential pressure meters.

As these meters are adversely affected by disturbed conditions on the upstream side they must be inserted into a straight length of pipe, and the flow must be controlled on the downstream side.

Before putting into service, it is necessary to make sure that the damping chamber is full of water and the downstream control valve opened slowly, otherwise the sudden rush of fluid filling the pipeline will damage the turbine assembly.

No maintenance is required apart from periodical inspection of the mechanism, for example during shut down, and when replacing worn parts.

(E) VARIABLE APERTURE METERS

These instruments work on the principle of a constant pressure drop across the detecting element, the cross-sectional area through which the fluid passes varying in accordance with the rate of flow.

The simple form of this instrument, widely used as a rate of flow indicator for water, gas and oil, consists of a tapered glass tube, mounted vertically, with its larger diameter uppermost. Inside this tube is a float having a rim diameter slightly less than the smaller bore of the glass tube (Fig. 38). Under *no flow* conditions, the float rests at the bottom of the tube, but when in operation the float rises until its apparent weight is balanced by the differential pressure caused by the metered fluid passing through the annular orifice formed between the rim of the float and the bore of the tube. The position of the float as indicated on a scale is a measure of the rate of flow. The original design of float, still commonly used, had a number of triangular notches cut in its rim, which caused the fluid passing through the meter to rotate the float and keep it in the centre of the tapered tube. For this reason, this form of instrument is widely referred to as a "Rotameter".

These instruments are now available as recording and integrating flow meters. A tapered metallic or non-metallic tube is used, and, in one form the float carries a rod which varies the inductance of an electrical circuit. The variation of electrical output, which is related to the rate of flow, is measured by an electrical instrument. Alternatively, the float carries a magnet, which is followed on the outside of the tapered tube (of non-magnetic material) by a second magnet. This moving element operates a force balance pneumatic transmitter. General details concerning these electric and pneumatic systems will be found under **TRANSMISSION SYSTEMS**.

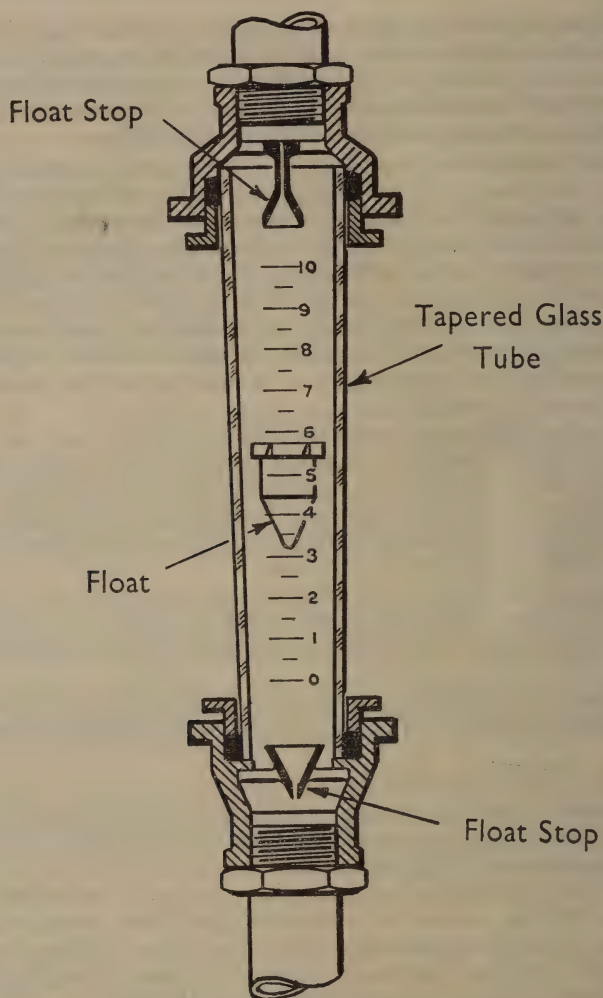


FIG. 38. Variable aperture flow meter.

The variable aperture meter which may be regarded as a general purpose instrument, is useful for metering corrosive and similar fluids that cannot be conveniently metered by other means. The design of the float and the materials of construction depend upon the nature of the application.

The smallest sizes of these meters can deal with minute flows, the largest size being suitable for pipelines up to about 6 inch bore.

A correction factor may have to be applied, as in the case of differential meters. When measuring the flow of gases in volume units, the correction factor is $\sqrt{W_m/W_a}$ and when measuring in weight units the factor is $\sqrt{W_a/W_m}$ where

W_m is the density of the fluid for which the meter is calibrated and W_a is the actual density at the fluid being metered.

When metering liquids, the factors for volume and weight units are

$$\sqrt{\frac{(W_f - W_a) W_m}{(W_f - W_m) W_a}} \quad \text{and} \quad \sqrt{\frac{(W_f - W_a) W_a}{(W_f - W_m) W_m}} \quad \text{respectively,}$$

where W_f is the density of the float. When calibrated in weight units for liquid measurement, the instrument is largely self-compensating for density variations, by making $W_f = 2W_m$.

The accuracy of registration is not affected by disturbed hydraulic conditions near the meter but, generally, the pipework must be altered to allow the fluid to flow upwards through the meter.

The detecting element, i.e. the flow tube and float, requires no maintenance except, perhaps, for occasional cleaning.

SOLID FUEL METERS

There are many machines on the market for the continuous weighing of solid fuel, as distinct from weighing in batches. The general principle involved in the operation of these machines is to supply the fuel to a constant speed belt conveyor, a length of which is "live". That is to say, it is supported by a counterbalanced weigh-bridge assembly. The change in weight of this section, caused by alterations in the amount of material passing on to it, is usually detected by a null balance measuring system. The counterbalancing force is continuously adjusted to maintain the system in equilibrium, the amount of adjustment required being a measure of the weight of fuel. By mechanical means, e.g. by detecting the position of the balancing mechanism at short regular intervals, the weight passed can be integrated on a counter.

Although these machines, (whose construction involves the use of knife edges, levers and tie rods) are highly accurate "instruments" their design and operation hardly fall within the bounds of the field referred to under the general term Instrumentation.

For the measurement of solid fuel, such a high degree of accuracy may not be required, since errors in *net* weight resulting from variations in the moisture content of the fuel will greatly exceed any weighing error. The *gross* weight of the fuel can be consistently measured with an accuracy within one per cent. but the difference between the gross and net weights can be up to 15 per cent. or more, depending on the amount of moisture in the fuel. The latter can vary rapidly with change in atmospheric conditions.

If the usual commercial tolerance of the order of ± 2 per cent. can be accepted (as it is for the metering of fluid flows) there is no reason why similar principles should not be employed. For example, the dead weight of the live section of the conveyor belt could be counterbalanced, the weight due to the material passing over the belt applied to a pneumatic force balance transmitter. (See **TRANSMISSION SYSTEMS** —pneumatic, p. 772.). Within the range of the equipment, the output air pressure of the transmitter would vary between 3 and 15 pounds/square inch, and this would be registered in terms of weight on a conventional form of measuring instrument.

For measuring the quantity of fuel fed to small boilers, an "inferential" method has been used successfully for many years. The operation of these "weighing" machines depends on the assumption that the density of any particular type of dry coal, e.g. bituminous, is practically constant in whatever district or country the coal is mined and is independent of the size of the lumps or particles. Therefore, if the volume is continuously measured, once the meter has been rated for a particular type of coal, it can be calibrated direct in weight units. It should be noted, however, that assessing weight by volume *versus* direct weight measurement is a controversial matter. In "Technical Data on Fuel", fifth Edition⁴, it is stated that "The bulk density of loosely packed coal is not a quantity reproducible to within 5 per cent., except under very closely controlled conditions of measurement. Compaction may increase the value by amounts up to 20 per cent." The publication gives tables of bulk density of loosely packed fuel which indicate that the density varies not only

with the grading of the coal but the dimensions of the container used for the measurement. In spite of this, many of these volumetric coal meters continue to give satisfactory service.

The principle of operation of a volumetric type coal meter, applied to a conveyor, is illustrated in Fig. 39. The deflection of the measuring door is

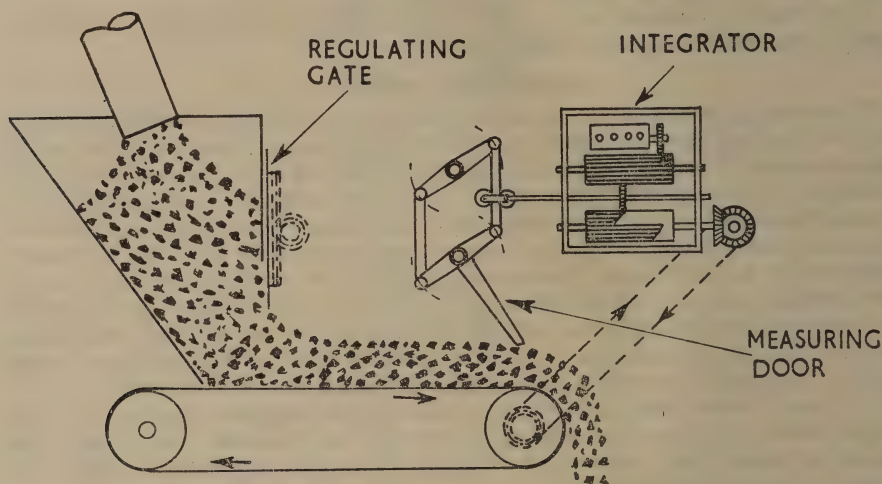


FIG. 39. Volumetric coal meter.

directly proportional to the volume of the coal, and this deflection, together with the speed of the belt, is transmitted to a counter which automatically and continuously multiplies these two variables. The counter, therefore, registers the total volume passed, and can be rated to register direct in weight units.

The method is applicable to all types of mechanical stokers, e.g. chain grate and ram stokers, and can also be used for coal supplied down pipes and chutes. In the latter cases, the measuring element is an endless chain which is carried downwards with the coal.

SMOKE DENSITY MEASUREMENT

The problem of smoke density measurement has hitherto been mainly a matter of ensuring compliance with the law in one form or another, the emphasis being on keeping within the law rather than on avoiding loss of efficiency. Growing realization that minimum smoke production and maximum fuel efficiency are complementary has focussed attention on the desirability of devising equipment that will control combustion as a result of smoke monitoring. Until such equipment is available and its adoption has become standard practice it is necessary for the industrial fuel user to have at his command devices or equipment that will go some way at least towards reducing the production of smoke to the desirable "faint brown haze" now accepted as a safe indication that combustion is proceeding satisfactorily. In Britain at least, the consequences of the Clean Air Act are such that smoke measuring devices and smoke alarms must be accepted as essential instruments.

The best known simple device for measuring the density of smoke issuing from a factory chimney is the well-known Ringelmann Chart. The equipment for using it consists of shade cards with grilles or lattices of black lines of different intensities, numbered 0 to 4, in accordance with the proportion of the surface covered by the black lines, number 4 indicating 80 per cent. coverage.

The charts were originally meant to be observed from a distance of 50 feet against the background of the smoke plume, the shade of grey of the plume being matched against the card whose shade most closely approximated to it. The cards are still used by smoke inspectors and by furnace operators as a check on the emission of smoke. For use, it is convenient if two observers take part in the operation, one to hold the cards in the required position between the chimney and his colleague and in such a position as to enable the latter to make a comparison.

Apart from the difficulty of applying the method in built-up areas, it suffers from a number of obvious disadvantages, particularly the state of the weather and the unpredictable human element. Furthermore, many smokes are not grey (i.e. "shades" of black); some may even appear almost white.

The density of the smoke is measured at a convenient point in the flue, stack, or uptake and the detecting element consists of two parts, the light projector on one side of the flue or stack and the receiver containing the light sensitive cell, on the other. The source of light is an electric bulb fed from a power supply through a constant voltage transformer. The beam of light is directed through the duct and on to the receiver by a lens; a second lens is in some cases used to concentrate the beam on to the light-sensitive element. The electrical output from the light-sensitive cell is proportional to the intensity of the light falling on its surface, which is determined by the density of the smoke in the intervening space. The electric output from the cell is thus inversely proportional to smoke density (Fig. 40). The output from the cell is measured on an electrical

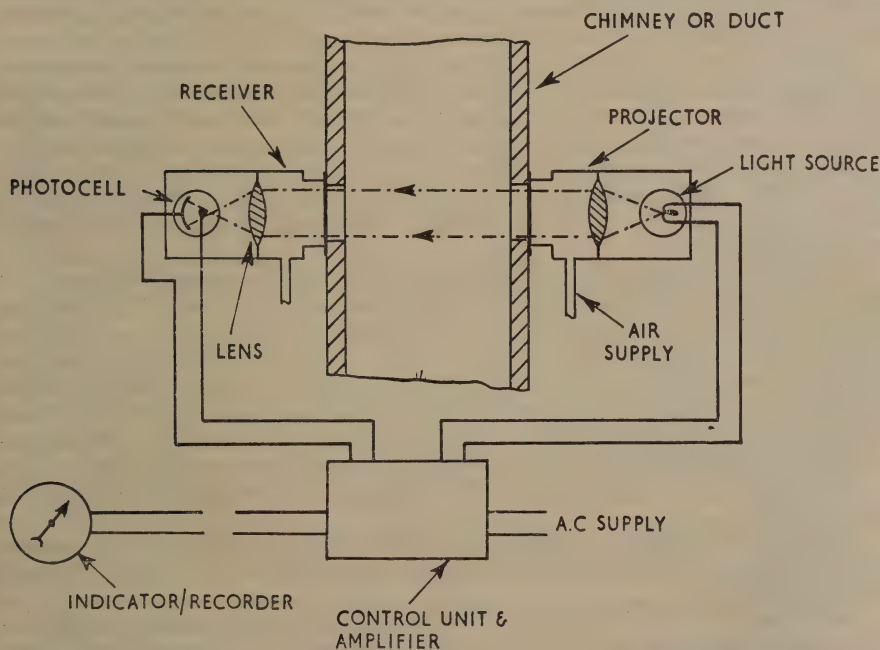


FIG. 40. Diagram showing principles of operation of smoke density meter.

From B.S. 2740. Fig. 1 Page 12

measuring instrument, indicating or recording, which may, if desired, be calibrated on site in terms of the Ringelmann scale. A comparison between the instrument reading and the Ringelmann scale is obtained only if the smoke is neutral gray or black, as would be the case in combustion applications. If

the smoke is white or coloured, the colour will affect the reading of photo-electric equipment.

Two types of cell are used. The first is known as the barrier layer or rectifier cell, which consists of a metal plate covered with a light sensitive material, e.g. selenium or cuprous oxide. This form of cell has the property of generating a small current flow, proportional to the intensity of light falling on it. The magnitude of the electrical current is very small, since all the energy to produce it is derived from the light source, but it is sufficient to be measured without amplification, e.g. on a direct deflection type indicator.

For various reasons it is not convenient to amplify the current from a rectifier cell. Therefore, to obtain a powerful output, the second type of cell, known as the emission cell, is used. This is a true photo-electric cell and consists of a glass envelope under a vacuum or filled with an inert gas at very low pressure. The glass envelope contains two electrodes, the cathode and the anode. The cathode, which is light-sensitive, is usually a plate, and the anode a single rod or ring positioned so as not to obstruct the light falling on the cathode.

The photo-electric cell does not generate a current flow, but if it is coupled into an electric circuit fed with a D.C. or rectified A.C. potential, with the cathode connected to the negative potential and the anode to positive potential a current flow is obtained in the anode circuit proportional to the intensity of light falling on the cathode. The current flow is minute and therefore an electronic amplifier must be connected into the circuit. This gives an electric output very much greater but in direct proportion to the input, which can be measured and indicated or recorded in smoke density units.

In some designs of equipment of this type, two photo-electric cells are used to give automatic compensation for any deterioration of the lamp which serves as the light source. The second photo-cell is mounted behind the lamp in the projector, the intensity of illumination falling on it being adjusted by a shutter, so that when there is no smoke the output from the two cells is equal. In this case the instrument measures the ratio of the two outputs, which is proportional to smoke density. Any deterioration of the lamp affects both photo-cells by the same amount.

To install the equipment, two holes are required on opposite sides of the flue or stack. These would be 2 inch to 4 inch in diameter. If possible, a position should be chosen at a point in the duct where a suction exists, so that the surrounding air will be drawn in to the duct, past the glasses protecting the lenses and so keep them clean. Alternatively, clean dry air from a suitable source can be continuously blown over the optical parts. These surfaces must be kept quite clean and facilities, therefore, are usually provided whereby, as an item of maintenance routine, manual cleaning can be carried out.

The ambient temperature at the projector and receiver should not generally exceed 115° F.

The measuring element, which can be fitted with an alarm, or can consist of an alarm only, can be mounted at a distance from the projecting and receiving units.

The definition of the terms *optical density* and *obscuration*, and recommendations concerning the use of smoke density measuring equipment, are given in B.S.2740, "Simple Smoke Alarms and Alarm Metering Devices"⁵ and B.S.2811, "Smoke Density Indicators and Recorders"⁶.

GAS ANALYSIS

From the point of view of the efficient use of fuel, flue gas analysis is of great importance. In the past, this analysis has been limited to the determination of the percentage carbon dioxide, but with improved techniques, it is

now possible continuously to detect and record the presence of oxygen in flue gases and also other gas mixtures. Since percentage of oxygen is a more reliable and fundamental guide to the percentage of excess air for combustion, the tendency is towards the wider use of oxygen analysers in steam-raising plant. Sometimes, for example, in cement manufacture, measurement of the carbon dioxide content of the gases is no guide to the efficiency of combustion, since large volumes of carbon dioxide are generated during the process; percentage oxygen measurement is then of first importance. The sampling of gases for analysis is dealt with in detail in Chapter 29, to which reference should be made. In view of the fact that the sustained accuracy of any automatic gas analysis equipment depends on the correct operation of the sampling system, it is desirable to emphasise some of the salient points concerning these systems.

For combustion control in a boiler plant, the sample of flue gas should be taken preferably before the economiser, or between the economiser and air heater. For overall heat balance calculations, it should be taken at the point where the final gas temperature is measured.

A representative sample of the gas should be continuously withdrawn from the flue. If possible, therefore, a sampling point should be selected where turbulent conditions exist. "Dead" spots, e.g. downstream of dampers or where stratification exists, should be avoided; stratification is less likely to occur in zones of high gas velocity. Also to be avoided are points where the gas may be diluted by air infiltration, e.g. through faulty brickwork.

The usual form of sampling probe is of uncooled metal through which the gases pass to the analysing unit. A mild steel tube may be used for temperatures below 540°C . For temperatures between 540°C . and $1,100^{\circ}\text{C}$., an alloy steel tube is required. Among other physical properties, the tube must have both mechanical strength at high temperatures, and resistance to thermal shock; it must also be non-absorbent, non-porous and resistant to corrosion.

It is the usual practice to fit a filter of refractory material, e.g. aluminium oxide, on the inner end of the tube to reduce the danger of blockage of the sampling system by soot, tar, etc., in the gas sample. The advantage of an internal filter is that condensation troubles are mitigated. An external filter of asbestos or glass wool may tend to become saturated unless it is heated. The sampling probe should be so installed that it slopes downwards from the internal filter. Since condensate from the cooling sample will drain away from the sampling probe this arrangement obviates difficulties that might result from small quantities of such substances as sulphur trioxide, which cause deposits and block the sampling probe. Armoured lead pipe is usually used for conveying the gas sample to the analysing unit. This form of pipe is resistant to corrosion, and is flexible, yet rigid enough not to sag without an excessive number of supports. The line also should slope downwards, to a point below the analyser, and terminate in a water seal, a connection being made in the pipe to the analysing unit. When site conditions call for a change in slope in any part of the line from the downward to the upward direction, a water seal should be fitted at the lowest point (see Fig. 41). In general, the slope of the sampling line in the direction of the sample gas flow should be downward for a fall in gas temperature and *vice versa*.

When site conditions call for the sampling probe to be mounted with its inner end pointing downwards, e.g. on a Lancashire boiler, the external vertical portion of the probe should be kept at a high temperature. It is important not to allow air to infiltrate through the sampling probe opening since this will cool the probe. Since the sampling point is generally under a negative pressure, some means of drawing the sample out of the flue must be provided. A water-operated aspirator is frequently used, e.g. a low rate of flow of water

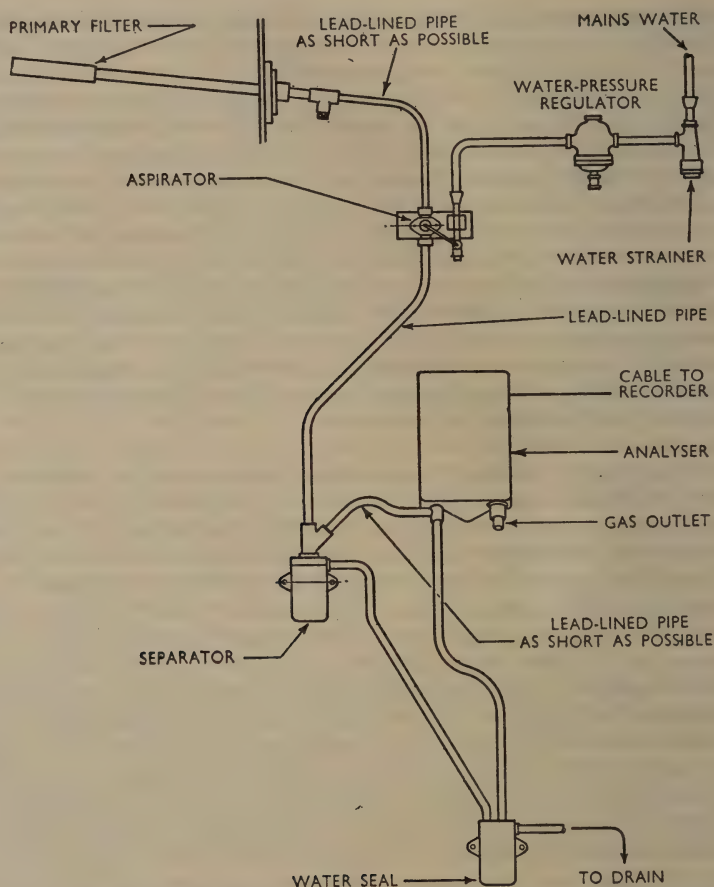


FIG. 41. Typical arrangement of sampling requirements for gas analysis.

is discharged into the top of a vertical portion of the sampling line, the water entraining the gas sample as it drops down the pipe and giving it up at a water-filled separator located below the analysing unit. Among other forms of aspirator is that of the water-operated Venturi type.

Other methods of extracting a continuous sample of the gas do not call for a supply of water. The aspirator may consist of a small Venturi tube located in the chimney. The suction generated in the throat of the Venturi is used to draw the sample through the analysing unit; this aspirator is mounted on the outlet side of the analyser. Alternatively, with some equipment, e.g. of the chemical absorption type, the gas sample may be drawn through the analyser by a gear pump. (See also Chapter 29.)

The capacity of the sampling system should be as small as possible, the minimum possible length of sampling line being used so as to reduce time lag.

CARBON DIOXIDE

The two systems most widely used for the detection of carbon dioxide are, respectively, the chemical absorption type and the thermal conductivity type. Other types operate on a centrifugal or density principle, but they are rarely encountered in industrial practice.

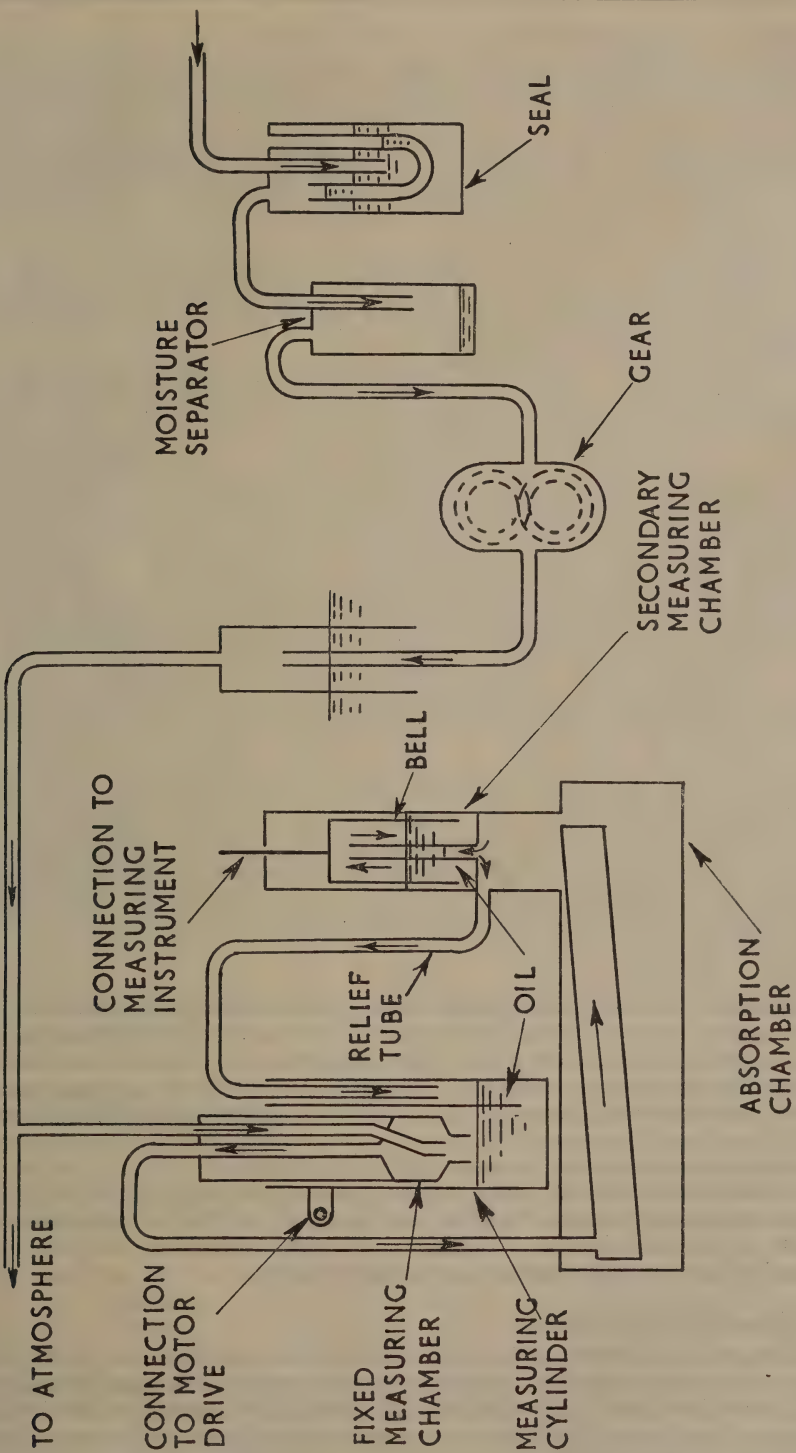


FIG. 42. Chemical absorption type carbon dioxide meter.

(A) *Chemical absorption type*

There are a number of different designs of equipment for continuously and automatically measuring the change in a given volume of gas after the carbon dioxide has been absorbed, e.g. by passing the gas sample through a solution of caustic potash. In one design the instrument gives an intermittent record, the pen continuously rising and falling back to zero and the variation in the carbon dioxide content being traced by the peaks of the pen record. In others, a continuous line is drawn.

An instrument of the latter type is shown diagrammatically in Fig. 42. A gear pump is used to pass the gas sample through the analysing unit; most of the gas sample is discharged to the atmosphere so that on the delivery side of the pump the gas is at atmospheric pressure.

The analysing unit consists of a measuring cylinder periodically raised and lowered by a motor. The measuring cylinder is partly filled with oil and surrounds a fixed measuring chamber with an open bottom just above which terminates a connection from the sampling line. As the measuring cylinder rises, the oil seals the open end of the connection from the sampling line, and as the cylinder continues to rise, the oil fills the measuring chamber and, in so doing, forces a known volume of gas from the measuring chamber through a baffle plate assembly contained in an absorption chamber. Here all the carbon dioxide is removed by the absorbing solution, and the residual gas is passed to a secondary measuring chamber. The secondary measuring chamber contains an oil-sealed bell, the upward movement of which is proportional to the volume of the residual gas and, therefore, inversely proportional to the volume of carbon dioxide absorbed. The displacement of the bell is used to position the recording mechanism. When the recording mechanism has taken up a position proportional to the percentage of carbon dioxide in the flue gas sample, it is clamped in position. The next step in the cycle is a fall in the measuring cylinder, the receding oil level first releasing the gas in the secondary measuring cylinder by unsealing the end of the relief tube and then the end of the connection from the sampling line, so allowing the fixed measuring chamber to fill with a new gas sample. The cycle is repeated and as the residue of the subsequent sample of gas is passed to the secondary measuring chamber, the registering mechanism is released to be re-positioned by the displacement of the oil-sealed bell.

Certain chemical absorption instruments also register the percentage of carbon monoxide *plus* hydrogen. In these, one cycle of operations directs the gas to a small electric furnace where these combustible gases are burnt, and then on through a combustion chamber; the next cycle passes the gas directly through the absorption chamber. Thus during one cycle the carbon dioxide, carbon monoxide and hydrogen are all measured and during the alternate one the carbon dioxide content alone is measured. The difference between alternate measurements represents the unburnt gases.

A conventional form of electrical transmitter can be incorporated in the instrument, so that a record and/or an indication of the percentage carbon dioxide can be obtained at a distant point, e.g. on a panel carrying other measuring instruments associated with the process.

(B) *Thermal Conductivity type*

This method of detection of the presence of carbon dioxide in a gas depends on the fact that the thermal conductivity of a gas depends upon its composition. For this method to be used satisfactorily, the thermal conductivity of the gas to be detected must have an appreciably different value from that of the other gases, i.e. carrier gases, which form the mixture, as is the case in a

flue gas. In addition to carbon dioxide, the main constituents of the gas are oxygen and nitrogen, both of which have approximately the same thermal conductivity, which is approximately twice the thermal conductivity of carbon dioxide.

The other important constituent of flue gas is water vapour, the thermal conductivity of which is approximately the same as for carbon dioxide. Therefore, the effect of variations in water vapour should be eliminated by either drying or saturating the gas sample before analysis.

Another gas which may be present in significant quantities is hydrogen and this, due to its high thermal conductivity, will cause an error in measurement (a low reading will be obtained). However, the presence of hydrogen in a flue gas is a sign of inefficient combustion, and steps would have to be taken immediately to eliminate it. Means are available for measuring the percentage of hydrogen *plus* carbon monoxide that may be present. The presence of the latter gas will not have any significant effect on the accuracy of the carbon dioxide percentage reading, since its thermal conductivity is approximately the same as that of air (oxygen *plus* nitrogen).

The method used for measuring the thermal conductivity of the gas sample is as follows: After drying or saturating, as the case may be, it is drawn through a measuring cell containing a platinum resistance wire heated by a stable A.C. electric supply. The temperature attained by the wire will depend on the rate at which it loses heat through the surrounding gas, and since the resistance of the wire depends on its temperature, the resistance will be directly related to the thermal conductivity of the gas sample flowing through the cell and, therefore, proportional to the percentage of carbon dioxide it contains.

The measuring cell forms one arm of a Wheatstone bridge, and since the changes involved are small, the other arm of the Wheatstone bridge contains a reference cell similar in construction to the measuring cell but sealed and filled with a reference gas, e.g. air, having thermal conductivity properties similar to those of the gas being analysed. Voltage and ambient temperature fluctuations affect both cells to the same degree and cause no disturbance to the electrical balance of the bridge. The electrical out-of-balance of the bridge can be detected and registered in terms of percentage of carbon dioxide by a direct-deflection-type electrical instrument, or it can be coupled into a potentiometer circuit which forms part of a standard null balance form of registering instrument.

Fig. 43 shows a typical gas analyser and sample gas flow circuit, the electrical circuit, in simplified form, being illustrated in Fig. 44.

To measure, in addition, the percentage of carbon monoxide *plus* hydrogen, the gas sample, having passed through the carbon dioxide measuring cell, enters a combustion chamber where the two unburnt gases are oxidised on the surface of a hot platinum wire, being converted to carbon dioxide and water vapour respectively. The gas sample is then passed to a second measuring cell of the type already described, a second Wheatstone bridge network being used. The difference in the two readings is a measure of the percentage carbon monoxide *plus* hydrogen.

As mentioned earlier, the use of an electrical measuring unit enables one of these to be used in conjunction with a number of detecting elements; carbon dioxide gas analysing equipment is no exception to this rule. A number of analysing units, each incorporating a measuring and reference cell and connected to different sampling points, can be used in conjunction with one multi-point measuring instrument. Instruments of this description are also available which record, for example, on a single two zone chart, both the temperature of the flue gas and the percentage of carbon dioxide it contains.

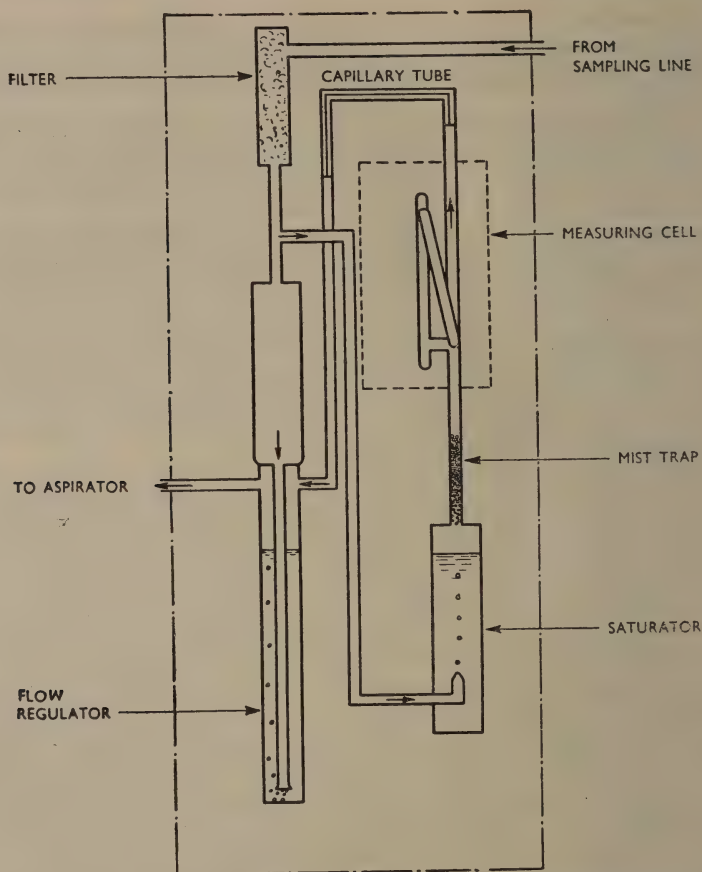


FIG. 43. Gas flow circuit through analyser of thermal conductivity type carbon dioxide meter.

OXYGEN

Most industrial equipment of this nature makes use of the magnetic properties of gases for its operation, a "magnetic wind" or force principle being employed. All gases are influenced by a magnetic field, either seeking the weakest part of the field—diamagnetic gases—or the strongest part of the field—paramagnetic gases. Most gases are diamagnetic, the two notable exceptions being oxygen and nitric oxide which are strongly paramagnetic, but nitric oxide is very much less paramagnetic than oxygen. Provided the properties of the carrier gases do not vary within wide limits, and the gas mixture does not contain an appreciable amount of nitric oxide (and flue gases fall within this category) this magnetic phenomenon can be used for the determination of the percentage of oxygen to a high degree of accuracy.

(A) *Magnetic wind type*

In this form of equipment, the gas sample is drawn through a measuring cell which may consist of a hollow ring with a diametral connecting tube (see Fig. 45). Wound on this tube and adjacent to each other are two platinum resistance wires which form the opposite arms of a Wheatstone bridge. These two resistances are heated by an electrical current, and one half of the diam-

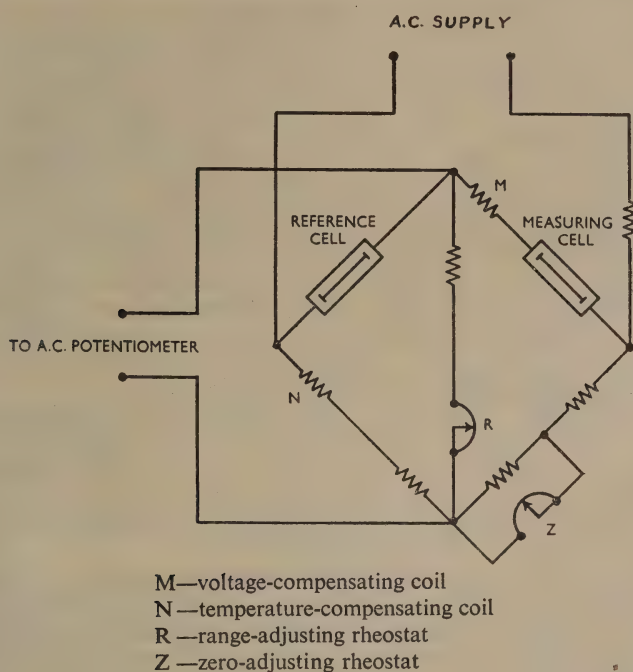


FIG. 44. Simplified wiring diagram for thermal conductivity type carbon dioxide meter.

etral tube is subjected to a magnetic field derived from a powerful permanent magnet. When a gas containing oxygen is passed round the annular ring, it is drawn into the diametral tube where its temperature is raised, this having the effect of reducing its susceptibility; i.e. its paramagnetism is reduced, and it is replaced by cooler gas, a continuous flow of gas being obtained through this tube. The winding on the inlet side of the tube provides the energy for heating the gas, so its temperature becomes lower than that of the winding on the outlet side of the tube. The resultant difference in resistance of the two windings causes an electrical out-of-balance of the Wheatstone bridge which is measured by a null balance potentiometer instrument in terms of percentage of oxygen.

The temperature of the analysing unit can be kept constant by a thermostat, or an electric resistance thermometer can be incorporated into the electric circuit to give automatic temperature compensation. Only a small proportion of the gas flows through the analysing unit, the remainder being discharged into the atmosphere. The rate of flow through the analysing unit is controlled.

(B) Force type

In equipment working on this principle, the same general means as those already described are used for dealing with the sample flow, the temperature of the analysing unit, etc., but the measuring cell contains a detecting element in the form of a "dumb-bell" suspended on delicate fibres. The detecting element is subjected to a strong non-uniform magnetic field, produced by a permanent magnet. If the gas passing through the cell is more paramagnetic than the detecting element, the latter is forced out of the region of maximum magnetic intensity, and *vice versa*. The magnitude of deflection of the detecting element is thus a measure of the percentage of oxygen in the gas.

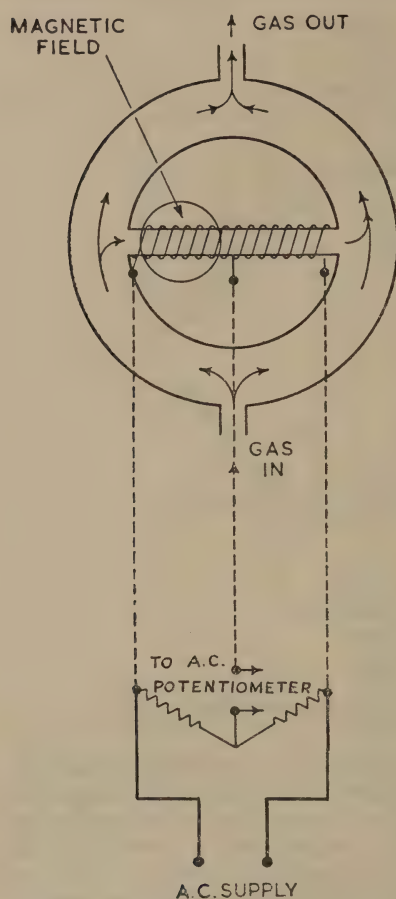


FIG. 45. Diagram of measuring cell of magnetic wind type oxygen meter.

The deflection of the detecting element may be measured without subjecting it to any load, by reflecting a beam of light from it on to two photo-electric cells; the general principle of operation is shown in Fig. 46. As the detecting element deflects, the ratio of light intensity falling on the two photo-electric cells alters and consequently changes the ratio of the output potentials from these two cells. The out-of-balance potential is amplified and registered, in terms of percentage of oxygen, by an electronic recorder. The measuring element can be mounted at a distance from the analysing unit.

For checking gas analysing equipment, standard portable equipment is used, e.g. the Orsat. To check the equipment over its whole range, gases of known composition must be passed through the analysing unit.

Maintenance consists of replenishing chemical solutions (absorption types), attention to water seals, saturators, filters, etc., and normal routine duties associated with all types of recording and indicating equipment, whether they be of the mechanical or electric type. An item of vital importance is that of keeping the sampling system in a clean condition and preventing the ingress of air by making sure all the joints are sound. The primary filter may be cleaned by blowing through the sampling system with low pressure compressed air. Certain filtering media, e.g. of refractory materials, are damaged by moisture; therefore they must always be

kept in a dry condition. Analysing units must be mounted in a position where they are not subjected to draughts and ambient temperature variations, and must be protected against vibration.

No mention has been made of other systems now available for analysing industrial gases, as for example, the infra-red method which is suitable for hydro-carbon and similar gases—but not for the detection of oxygen. These instruments are being developed rapidly and are proving to be of very great value, particularly in specialized industrial fields.

TRANSMISSION SYSTEMS

The transmission of the value of pressures, temperatures, flows and other variables over a distance is of growing importance with the expansion of industrial instrumentation. It enables the values of these variables to be assembled and registered at one central point where they can be kept under observation by the engineer in charge without his having to visit the individual measuring points. Even in a small factory or boiler house, centralization of records is of assistance in maintaining maximum efficiency in the operation of the plant.

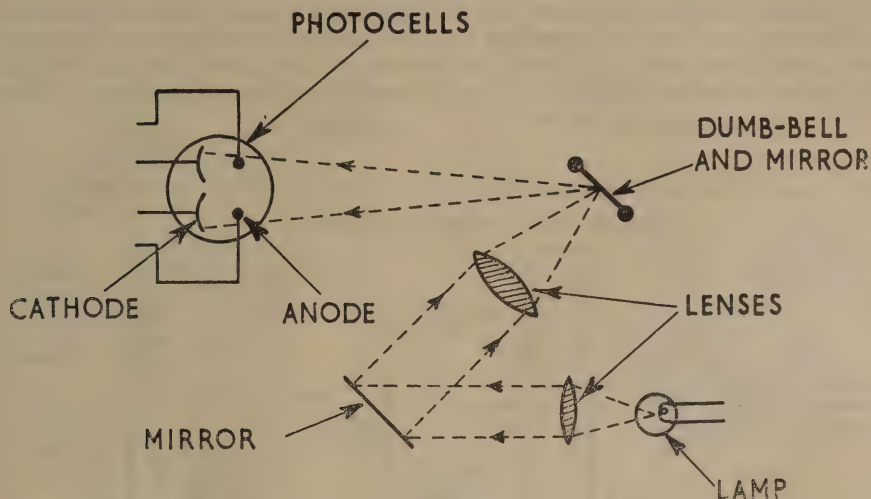


FIG. 46. Diagram showing principle of operation of force type paramagnetic oxygen meter.

Two systems of transmission are in current use—electrical and pneumatic. In the former, the value of the physical variable is converted into an electrical quantity, the receiver being an electrical measuring element which registers the input in the appropriate units, e.g. of temperature, flow or percentage of carbon dioxide, etc. Some detecting elements, such as a thermocouple, are a “natural” electrical generator and no conversion element is required. Others, for example, an orifice plate for flow measurement, are not. It should be noted that a standard differential pressure flow meter installation may be regarded as incorporating a transmission system, since the measuring element can be located at a distance from the point of measurement. The same remarks can be applied to a simple pressure measuring installation. However, in instrumentation these systems are not regarded as falling within the category of distant transmitters, since the “transmission distance” is strictly limited.

In the pneumatic system, the value of the physical variable must be converted to a single air pressure, the receiver being a conventional form of pressure-measuring element. As modern technique uses a standard pressure range of 3 to 15 pounds/square inch irrespective of the application, a transmitting element is always needed.

Due to the flexibility of electric transmission systems, and the ease with which a number of different values can be registered on one instrument, these are more widely used in industry than pneumatic systems. As a general rule, pneumatic systems are confined to special applications and to those where dangerous atmospheres make it desirable to avoid the use of electrical equipment.

Electrical Systems

Where the detecting element output is not electrical in character, a common method employed is to use a conventional form of measurement element and adapt this, for example, to vary the resistance of an element contained in the electric circuit. For example, in a differential pressure form of flow meter, instead of operating the registering mechanism, the instrument moves a contact arm over a resistance wire, which causes the current flow round the circuit to vary in proportion to the rate of flow. This transmitter, which may

be of the mercury U-tube form, can also operate a pointer indicating the rate of flow on a scale, and incorporate a cam mechanism or similar device to make the current flow round the circuit proportional to the rate of flow and not the differential pressure (Fig. 47). In an alternative design of mercury U-tube

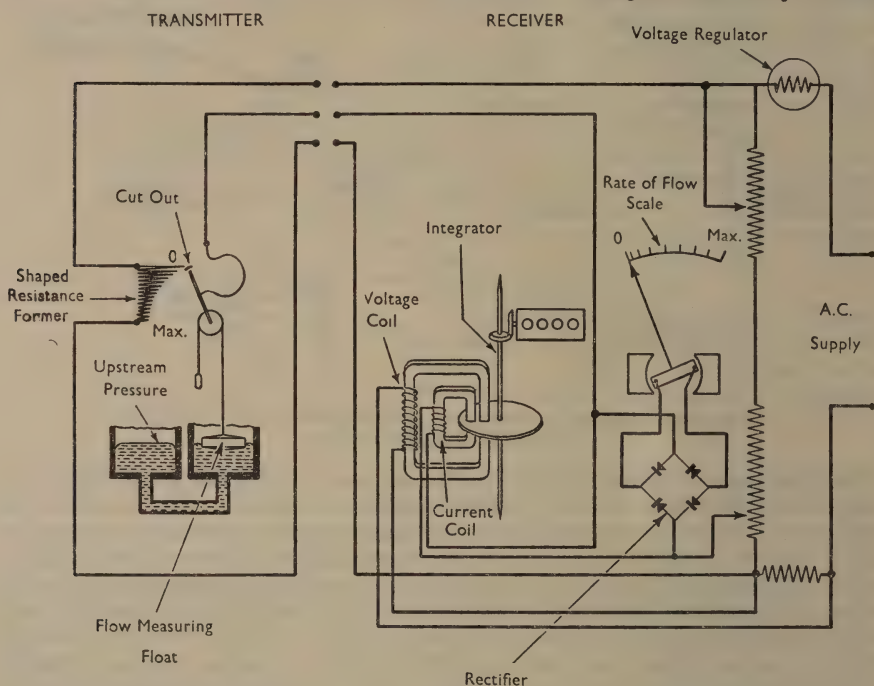


FIG. 47. Simplified wiring diagram of typical electric transmission scheme—applied to flow measurement.

transmitter, which may be regarded as being of the "blind" form, conductor rods are used instead of a wire-wound resistance former, each rod being separated from its neighbour by a resistance. The rods are of different lengths and are suspended vertically in the lower pressure chamber of the U-tube. To economise in space, the conductors are positioned in spiral form (when viewed in plan). A rise in mercury level with increase in flow rate causes the mercury to impinge on a progressively larger number of rods, shorting out the resistances and causing an increase in current flow round the circuit, (Fig. 48).

There are other ways of obtaining the required conversion to an electrical quantity, as for example the induction method used on variable aperture flow meters. All these methods can be used for other forms of measurement, e.g. pressure—the basic principles remain unaltered.

As mentioned earlier in this chapter, direct deflection type indicators, and also recorders, are widely used, as are electrical integrators (flow measurement). However, they are being replaced to a considerable extent by null balance type instruments which can give a very powerful output directly related to a very small electrical input. As the powerful output is obtained from a fractional horsepower motor, the instrument may be regarded as an amplifier.

Null balance instruments may be divided into *mechanical* and *electronic* forms—the electronic form is gradually superseding the mechanical.

In the mechanical form of self-balancing instrument, a galvanometer is used to detect the electrical out-of-balance. Irrespective of the type of circuit

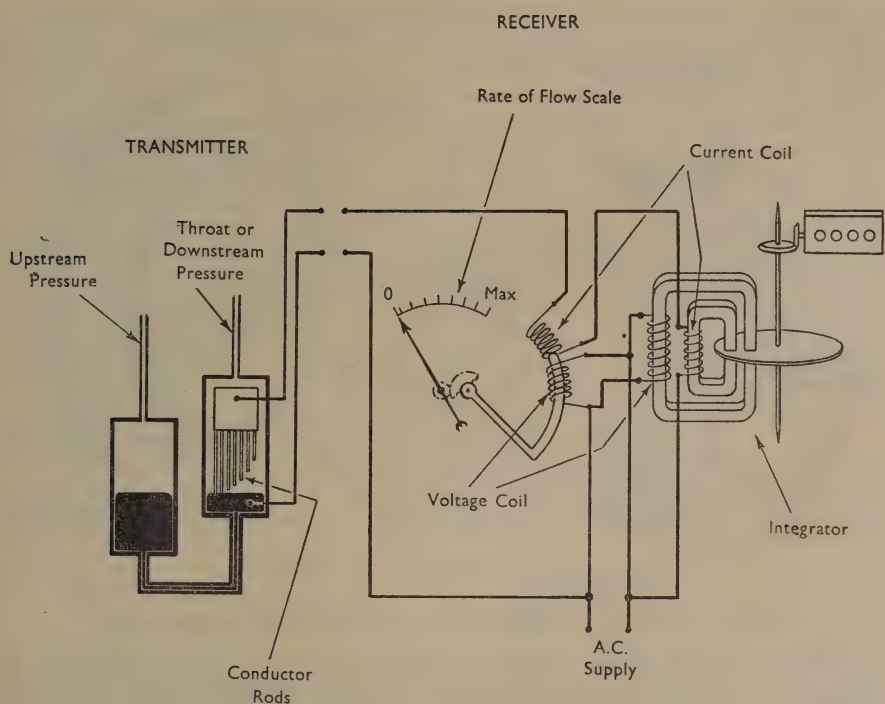


FIG. 48. Alternative scheme to that illustrated in FIG. 47 for electric transmission of flow.

(Wheatstone bridge or potentiometer) the same mechanism is employed. The action of the mechanism is cyclic, a number of operations being repeated every few seconds, so that the receiver slide wire contact arm is adjusted in small steps to maintain the circuit in electrical balance. The operation of a typical mechanical self-balancing instrument is as follows.

The galvanometer pointer, swinging in a horizontal plane, is first clamped in position. The position of the pointer is then detected by two arms that approach it from opposite sides. If the galvanometer pointer is clamped in a deflected position, indicating that the circuit is out of balance, one of the arms will impinge on the pointer before the other, and this latter arm will have a greater distance to travel before it makes contact with the pointer. In moving this additional distance, the arm displaces a pivoted clutch lever by a corresponding amount and, *via* a cam rotated at constant speed, the clutch lever is brought into contact with a clutch plate. Immediately contact is made with the clutch plate, the clutch lever is returned to its undeflected position by two other cams.

In bringing the clutch lever back to its undeflected position, the clutch plate is rotated a corresponding amount. The clutch plate spindle carries a disc round which is mounted the slidewire, the contact arm being fixed so that the effect of the rotation of the clutch plate is to alter the position of the contact relative to the slidewire in the direction to restore electrical balance. The final result would, of course, be the same if the slidewire were fixed and the position of the contact arm were altered. The registering mechanism (indicator, recorder, and if applicable, integrator) is mechanically coupled to the clutch plate spindle, so that this moves in unison, (Fig. 49).

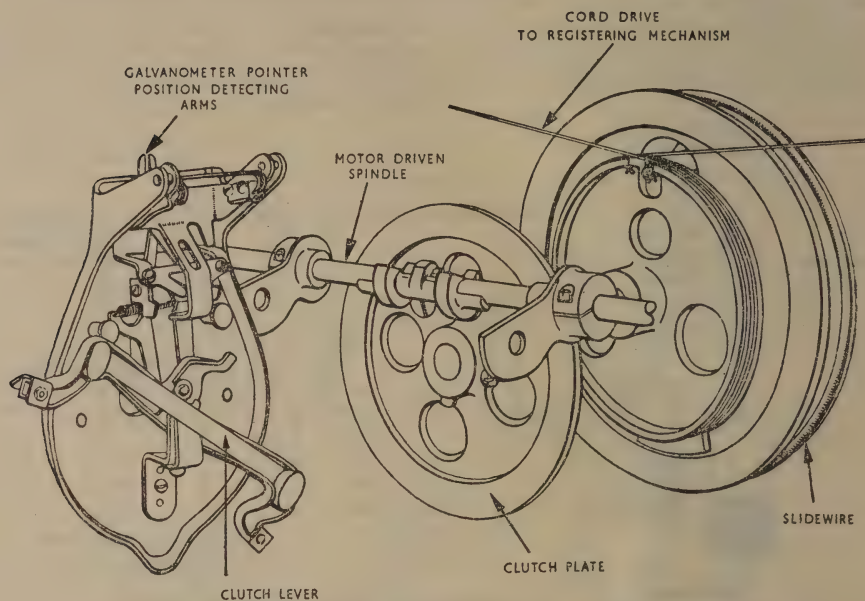


FIG. 49. Mechanism of null balance electrical measuring instrument.

If a large change in the measured quantity has taken place, one cycle of operations as described may be insufficient to bring the circuit back into electrical balance. Therefore, during the subsequent cycle, the galvanometer pointer will again be deflected and a further correction will take place. For example, if a sudden change in the measured quantity from (say) zero to its maximum value has taken place, a number of cycles will be required to attain a balance, and as the duration of each cycle is of the order of two seconds, the time required to attain balance may be between 20 and 30 seconds.

All the power for operating the auxiliary mechanism is derived from a fractional horse power motor incorporated in the instrument, and for operating this a mains electric supply is required. If required (e.g. for flow transmission), the transmission circuit can be energized from the same supply.

It is important to note that, in addition to giving a powerful output, the null balance principle of measurement renders the accuracy of registration independent of the individual characteristics of the galvanometer.

The electronic null balance principle minimizes the wear and friction inherent in the mechanical form. Also, for all practical purposes, balancing is a continuous operation—full scale deflection can be obtained in a matter of two or three seconds, in comparison with 20 seconds or so for the mechanical form of instrument. This is of importance in multi-point recording.

In most electronic null balance type measuring instruments, a galvanometer is not used, the electrical input (the value of which varies with that of the measured quantity), being greatly magnified by an electronic amplifier so that the output can drive an A.C. reversing motor which continuously performs the balancing operation.

Electronic Amplifiers

The theory of electronics is not within the scope of this book, but in view of its growing importance in instrumentation, an elementary description is given of the basic principles of operation of electronic amplifiers.

Amplification is obtained by means of a valve, the simplest of which for this application being the *triode* (three electrodes). An electronic valve consists of an evacuated glass envelope containing the electrodes. In the triode, these are the cathode, the grid and the anode, as shown in Fig. 50. In practice a concentric form of construction is used, the cathode being surrounded by the grid, which consists of a fine metal screen, and this, in its turn, is surrounded by the anode. The cathode is kept hot by an electric heater, and this causes it to emit electrons, which constitute an electric current. Under normal operating conditions the anode potential is kept positive and, the grid slightly negative, relative to the cathode. Under these conditions, the electrons emitted by the cathode are repelled by the grid, but some pass through the grid and are collected by the anode to form the anode current. The proportion of electrons passing through the grid depends on the grid potential, a very small change in which causes a large change in anode current. In other words, a very small electromotive force in the grid circuit can control a relatively large electromotive force in the anode circuit. The manner in which this principle is used for amplification is shown in Fig. 50.

The low tension battery maintains the grid at a negative potential with respect to the cathode, and when no input signal is applied to the grid, the anode current, which forms the output, is constant, having a value determined

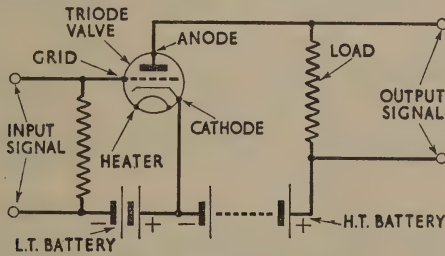


Fig. 50. Simplified circuit for electronic amplifier.

by the load resistance and the voltage of the high tension battery. When an input signal is applied, as the grid becomes more positive, the anode current increases, and *vice versa*.

Example

Suppose the load resistance is 15,000 ohms and an input signal has the effect of making the grid 1 volt less negative. If this has the result of increasing the anode current by 1 milliampere, since the load resistance is 15,000 ohms, from Ohm's Law, the change in voltage across the load will be $0.001 \times 15,000 = 15$ volts. That is to say, an input change of 1 volt causes an output change of 15 volts, so that the "gain" of the amplifier is 15. The maximum possible gain is known as the amplifier factor (μ), and for a high μ triode, the value is of the order of 70. Such a small amplification is sufficient for comparatively few applications, but by using a number of amplification stages in cascade (the output from one forms the input to the next stage) in the low power region (which covers most if not all instrument applications) an amplification of (say) one million can be obtained with a relatively simple electronic circuit.

In Fig. 50 the power supply is shown as being derived from batteries; in practice the mains supply would be used for this purpose.

A simplified Wheatstone bridge circuit as would be used in temperature measurement, and incorporating an electronic measuring element, is illustrated in Fig. 51. The out-of-balance voltage forms the input to the amplifier,

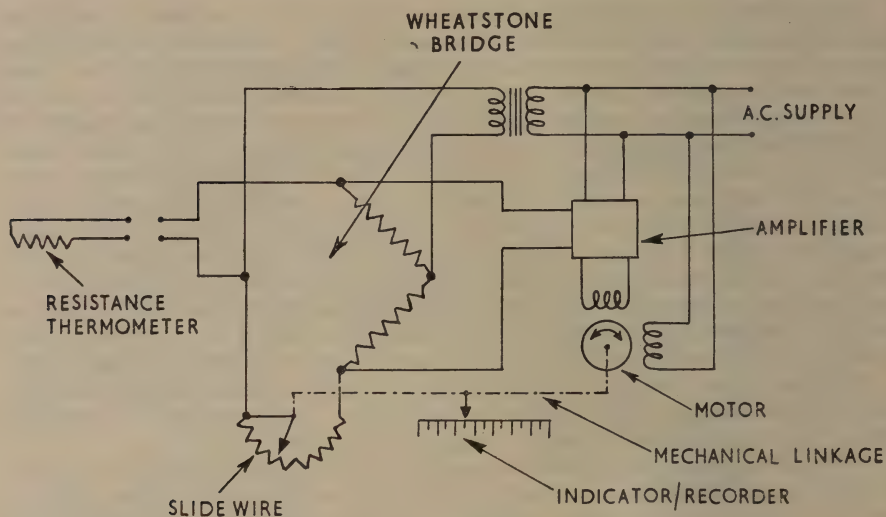


FIG. 51. Simplified circuit for an electronic resistance thermometer.

the electrical output from which is sufficient to drive the reversible A.C. motor coupled mechanically to the slidewire contact arm. The direction of rotation of the motor is determined by the "direction" of out-of-balance. Since the balancing operation is acting continuously, the actual temperature is being registered at all times with virtually no delay. The accuracy is not affected by the characteristics of the amplifier.

For various technical reasons, it is desirable to use alternating current for amplification. Therefore, when the input is D.C. (as for example in temperature measurement using a thermocouple and potentiometer circuit) means are provided for converting the D.C. input to A.C. A method commonly employed is to use a vibrator which, by oscillating at the mains frequency, "chops" the direct current into alternating pulses.

Similar circuits can be used for the electric transmission of any variable quantity over a distance, using a suitable transmitter which gives a change in an electrical quantity, e.g. voltage or current, proportional to the value of the measured variable.

When a potentiometer circuit is used, the input e.m.f. must be balanced by a constant e.m.f. from another source, generally a battery. To correct for change in battery voltage with time, the circuit must be standardized at regular intervals by comparing the battery e.m.f. with that generated by a standard cell, and adjusting the battery e.m.f. by means of a rheostat. When a null balance instrument is used, the standardization is done automatically by the instrument at regular time intervals. In electronic equipment of recent design a "reference unit" is incorporated in the circuit, which ensures that the circuit is at all times fed with a constant voltage; as the supply is derived from the mains, batteries are not needed. Other means of obtaining the same result, e.g. magnetic amplifiers, are not yet in common use.

Pneumatic transmission systems

For this form of transmission, what is known as a *force balance* unit may be used. Since a conventional form of measuring instrument need not be used at the transmitter end of the system, these units are also sometimes referred to as "blind" transmitters.

The transmitter, an example of which is illustrated in diagram form in Fig. 52 consists of a pivoted beam arm, to one end of which is applied

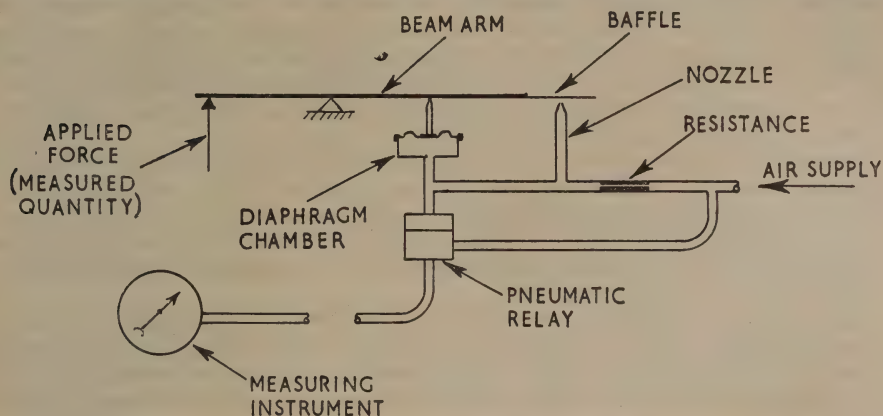


FIG. 52. Diagram of pneumatic transmitter.

the force, the magnitude of which is directly proportional to the quantity being measured. The other end of the beam arm carries a baffle facing a nozzle fed with compressed air through a resistance, so that the air pressure within the nozzle system is determined by the position of the baffle. As illustrated, the nozzle system is connected to a diaphragm chamber, the diaphragm exerting a force on the beam arm in opposition to the force exerted by the measured quantity. The nozzle system is also connected to the distance measuring instrument, i.e. the receiver, which consists of a pressure gauge. Referring to Fig. 52 with the system in equilibrium, if the force exerted by the measured variable increases, the beam arm tends to deflect in a clockwise direction, the baffle approaches the nozzle restricting the bleed to the atmosphere; hence the air pressure within the nozzle system increases. This increase in air pressure on the diaphragm increases the turning moment resisting the applied force, a state of equilibrium being again reached, the air pressure within the nozzle system, and consequently that being registered by the receiver, being proportional to the applied force. The reverse action is obtained when the applied force decreases. To obtain quick response to changes in the value of the measured variable, it is the usual practice to apply the transmitter pressure to the measuring instrument by means of a relay. The function of the relay is to provide a relatively large volume of air at a pressure determined by the transmitter.

The mechanism is so designed that full change in air pressure is obtained for a baffle deflection of the order of 0.001 inch—the diameter of the nozzle outlet is of the same order of magnitude. There is thus, virtually no displacement of the mechanism, yet the output air pressure varies directly as the applied force, i.e. the value of the measured variable. All pneumatic transmitters of this form are now designed to have an output range of 3–15 pounds/square inch, that is to say, for zero value of the measured variable, the output air pressure is 3 pounds/square inch, and for its maximum value, 15 pounds/square inch. By using the “negative feed back” principle described above, the accuracy of transmission is not influenced by the characteristics of the diaphragm, nozzle and resistance. In such applications as flow measurement by differential pressure, the difference in pressure can be applied direct to the transmitter. In other instances, it may be necessary to convert a displacement into a force, e.g. by using a spring.

In a similar form of pneumatic transmitter, using a baffle and nozzle and a negative feed back system, the measured variable must be expressed as a mechanical displacement. Pneumatic transmitters of this type, therefore, are used in conjunction with conventional forms of measuring instrument. For example, a pneumatic transmitter of this description could readily be coupled up to an electrical null balance temperature-measuring instrument. To distinguish these transmitters from the force balance form, they are commonly known as "position balance" transmitters.

Some electrical transmission systems are limited by the length of the transmission lines and their resistance. In installations of this description, the manufacturers of the equipment must, therefore, be advised of the transmission distance, and their advice concerning the type of cable to use should be followed. Only in exceptional circumstances will transmission distance be the limiting factor in factory practice.

Some electrical transmission circuits are particularly susceptible to electrical interference. For that reason, multi-core cables carrying high voltages should not be used. In all cases, a separate multi-core cable devoted solely to the transmission circuits is necessary; this must be protected against outside interference.

In many instances the transmitter, when it is of the conventional measuring element form with the electrical portion forming an additional element, will require protection against damp and other unfavourable ambient conditions. The same degree of protection is required as for a mechanical form of measuring element. These remarks do not apply to a blind type of transmitter, e.g. the contact rod type of electrical flow transmitter.

If the normal electrical practice is adopted for the wiring, and unsuitable zones, e.g. of high temperature, are avoided, satisfactory operation of the equipment will result. For sustained accuracy the readings of the receiving instrument should be checked at regular intervals against the transmitter so as to avoid the persistence of electrical faults.

It is vitally important that electrical instruments, and especially those of the mechanical and electronic null balance form, receive skilled attention. Little maintenance is required, but what is required must be of a high order.

The maximum transmission distance for pneumatic transmitters is of the order of 1,000 feet. Small-bore impulse pipes, e.g. of copper, are used to convey the pressure from the transmitter to the receiving instrument. It is of vital importance that all connections in the pipe run be absolutely pressure-tight. While there is practically no flow of air through the system it is desirable, in laying the impulse pipe, to avoid zones of low temperature and so prevent condensation in the impulse pipe.

Blind force balance transmitters are so designed that they can be mounted at the measuring point without needing any protection. However, when the transmitter must incorporate some element for converting the value of the physical variable into a pressure, this mechanism may need protection.

Since position balance pneumatic transmitters form part of a conventional form of measuring element, protection against dirt, dampness, etc., is required. All pneumatic transmitters require a supply of clean compressed air at the transmitting point.

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CHAPTER 28

THERMOSTATIC CONTROL**THE PURPOSE OF THERMOSTATIC CONTROL**

THE purpose of thermostatic control of a heating installation, whether for space heating or for a manufacturing process, is to maintain constant temperature and to secure maximum economy in fuel consumption.

The factors involved are so variable that without some aid such as thermostatic control constancy of temperature cannot be expected, and overheating and waste of fuel are sure to occur.

Although some degree of constancy of space temperature or of process temperature can be maintained by manual adjustment of the primary source of heat and of its distribution to the space or process, the cost of doing this in terms of the time of one or more operators continually in attendance in addition to that of the indicating instruments, control valves and other equipment would be prohibitive. Nor could the level of effectiveness of a comparatively simple automatic control scheme be achieved. Automatic control devices sensitive to the immediate surrounding temperature conditions and others whose setting is automatically varied in anticipation of a change in one of the factors affecting the final process or space temperature, can do far more than any system of manual adjustment, not only in terms of fuel economy and constancy of control but also in terms of cost.

Effects of Plant Conditions on Control. No thermostatic control system can do its job unless the total heat available is sufficient. If it is found impossible to hold the temperature within the necessary limits by constantly making adjustments by hand, it may be safely assumed that the necessary heat balance does not exist. In such circumstances it is a futile waste of time to try to attain satisfactory control by automatic devices before the fault in the plant and perhaps fault in the firing technique have been rectified. The fundamental and essential part played by efficient combustion control, and by conservation of heat by adequate insulation, must not be neglected. It is impossible to lay too much emphasis on this aspect, as it is here that probably the commonest causes of unsatisfactory control occur, especially on steam-heated apparatus.

HOW THERMOSTATIC CONTROL OPERATES

The part played by thermostatic control can best be appreciated by considering the design of a typical heating installation and the factors that affect it. A space heating radiator installation is an excellent example to examine, in respect of its purpose, the conditions under which it has to operate and the result which it should achieve.

Buildings in Britain are artificially heated during the winter because the average outside temperature is too low for comfort and it is necessary to provide additional heat in homes and working spaces for the maintenance of health and essential bodily comfort.

The most desirable central heating installation is one that will provide constant comfort inside the building and maximum economy in fuel consumption, two closely related desiderata. The action of a thermostat in preventing excessive temperature not only adds to the comfort conditions in the building but at the same time prevents waste of fuel.

The condition mainly responsible for straining the resources of the central heating installation is that of inconstancy of the weather, which varies from day to day and between day and night. The result is that the fuel-consuming appliance cannot be a device for merely giving out a constant quantity of heat during the heating season; it must give a variable quantity of heat as dictated mainly by the weather.

Some idea of the variation in load with which a central heating plant may be called upon to deal can be gained from the fact that most installations in Britain are designed to maintain a space temperature of 65° F. for an outside temperature of 30° F. , that is, they are capable of raising the temperature by 35 degrees. But the average outside temperature during the heating season is approximately 43° F. ; consequently the boiler plant has a considerable margin when running on average load, since the heat required is proportional to the temperature rise which is an average of 22 degrees in this example. Whereas the average load on a boiler over the whole of the heating season might be 880,000 B.t.u./hr., it is increased to 1,400,000 B.t.u./hr. when the outside temperature falls to 30° F. Notwithstanding the fact that the maximum design load is based on an outside temperature of 30° F. , it is considered good practice to provide a margin of up to 25 per cent. of the maximum load to enable the plant to deal with extremely cold weather and to permit space temperature to be restored reasonably quickly after the plant has been shut down for a period, e.g., during a holiday. Thus if a margin of 20 per cent. over the designed maximum load is provided the boiler would be capable of an output of 1,680,000 B.t.u./hr. and the difference between this figure and the average requirement of 880,000 B.t.u./hr. is considerable. The fuel consumption in these typical circumstances can conveniently be kept at an economical level by automatic control.

An illustration of the varying rates of heat requirement is given by the graph, Fig. 1, which shows the record, A, of outside temperature during a week in December against the datum, B, of a desired space temperature of 65° F. During the period the outside temperature varied between 53° F.,

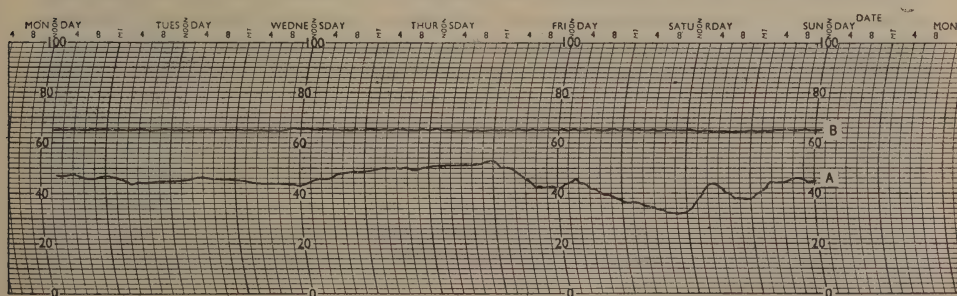


FIG. 1. One-week winter Thermograph Record.

requiring a rise of 12 degrees, and 32° F., requiring a rise of 33 degrees, the average during the week being 44° F., requiring a rise of 21 degrees.

A further condition affecting the problem is that the building may be subject to incidental heating varying with occupancy. For instance, a shop or school, or place of entertainment can be greatly affected in this way; also factory space temperature can be influenced to a considerable extent by the processes carried on in it. The heating effect of lighting which varies from building to building is another factor that must be considered. Furthermore, the geographical aspect of the building may affect the space temperatures in

different parts of a building. These factors of variable weather, and to a much lesser extent in the majority of cases variable incidental heating, show that if the installation is successfully to perform its primary function of maintaining a constant condition of comfort, it must be automatically controlled, and by a control which will cope with all these variables.

GENERAL APPLICATION OF THERMOSTATIC CONTROL

It is a comparatively simple matter to install thermostatic temperature controls to maintain constant comfort in the case of a space heating installation, or constant temperature for process work, by regulating the quantity of heat provided, proper account being paid to the variables that tend to disturb the condition of constancy.

The necessity for maintaining a constant temperature in many processes is very great; if the temperature varies by more than a small margin, not only will the material being processed be damaged but the time taken to perform the operation will be greatly extended. Automatic thermostatic control enables the planning engineer and the operator to work far more effectively than with manual control and the resulting improvement in the quality of work produced and the reduction in the time taken to produce it and in the cost of the fuel are very substantial.

Many combinations of thermostats, timing units, and other devices can be applied particularly to process heating control according to the type of installation, but the basic principles outlined still apply.

In the case of space heating installations the field is equally wide and in both types of installation there is every encouragement and practical assistance in the form of automatic temperature control devices to ensure that every heat unit produced from the combustion of any type of fuel can be made to perform its proper share of useful work.

BASIC CONTROL OF SPACE HEATING AND OF PROCESS HEATING

Since the purpose of a space heating installation is to provide a constant condition of comfort a device that can control the heat input to the building in response to the space temperature would seem desirable. Similarly, a process heating installation control problem would seem to call for a thermostat sensitive to the temperature of the particular process and arranged to control the heat input. Both of these suggestions are sound.

While the responsibility for controlling any space heating or process heating installation rests ultimately on a device in the space or process, the best result can be achieved by tackling the problem in two stages. The first is the control of the primary heat source so that the total heat input will generally balance the total requirement, and the second is the control of the distribution of the heat to the various spaces or processes so that the individual requirements of each can be satisfied.

By dividing the control in this way it is possible to take full account of all those variables that affect an individual space or process, and secure maximum economy by restricting the heat to the amount required for each. The various methods of controlling boiler output and heat distribution are described below.

CONTROL OF BOILER OUTPUT

It has been stated that the responsibility for controlling a central heating installation rests ultimately with a device in the space being heated, and first thought may suggest that a thermostat in the space acting directly on the boiler would have the desired effect. In point of fact, it is unsatisfactory to control the boiler output directly by the space temperature because the time lag between a change in demand by the thermostat and the response in the

space from a changed boiler output is so great that considerable overshooting and under-running of the designed space temperature is the result. Furthermore, when the space thermostat controls heat distribution, the difficulty of finding an average position for a *master thermostat* is considerable and requires a good deal of thought even in the two-stage method of control.

Most automatic boiler firing appliances burning solid fuel, oil or gas are designed to feed the boiler at one or a number of steady predetermined rates, and control of the heat output is effected by stopping and starting the feeding mechanism under the control either of a thermostat in the boiler water or of a steam pressure switch, the length and frequency of the feeding impulses depending upon the load on the boiler.

The thermostat can, according to circumstances, be of the type either controlling at a fixed temperature, or capable of being changed manually to suit the particular load requirement, or it can be of the compensated type having a fixed basic setting with automatic variation of the control point by a device sensitive to the outside weather. The first two are generally used for process heating boilers and dual space-process heating boilers, whilst the last is used for those boilers used solely for space heating.

Whichever type is used it essentially comprises an electric switch, arranged to stop and start the firing appliance by one or other of the control methods.

CONTROL OF MECHANICAL STOKERS

Where the boiler is fed with solid fuel through a mechanical stoker, particularly of the underfeed type using screw or ram feeding, control of boiler output is achieved through regulation of the quantity of coal fed to the boiler by stopping and starting the stoker motor. This motor drives the worm or ram that feeds the coal into the retort and the fan supplying the combustion air. Air and coal feed rates are initially balanced for maximum combustion efficiency in the setting of the stoker and the thermostat does not disturb this balance since both coal feed and air supply are started and stopped at the same time.

With most types of underfeed stoker the rate of coal feed when the motor is running is kept constant, but it can be pre-set according to the particular installation. With other types of underfeed stoker it is possible to select automatically, by means of an additional thermostat, one of two alternative rates of coal feed, the choice between these two rates being controlled by the boiler load at the particular time.

With some of the bigger installations, particularly those using steam boilers, induced or forced draught fans are sometimes used in conjunction with the stoker and these are automatically controlled in proper sequence with the stoker motor.

To prevent the fire from dying out when the boiler load is so small that it can be satisfied by short and infrequent supplies of fuel, it is usual to fit a kindling control which comes into operation when the thermostat would otherwise stop the stoker motor. The kindling control consists of a small electrically-driven clock which causes the stoker motor to run for a period of perhaps five minutes in each 60 minutes (or otherwise as may be required). Its use is of particular value during the night when the plant may be banked down.

CONTROL OF OIL BURNERS

Oil is a popular fuel for space heating installations and the most popular type of oil burner is the pressure jet atomizing type. This can be controlled automatically by stopping and starting the motor operating the oil pump and fan and controlling the ignition device, the whole sequence of control operations being done through a control box specially designed for the purpose.

When the controlling thermostat calls for heat, the correct sequence of starting is carried through automatically and protection is afforded so that failure to establish the flame for any reason is followed almost at once by the electrical isolation of the burner, after which it is necessary to re-set manually a lock-out switch before a second start can be made.

Failure to establish the flame on starting can be due to a number of causes. For instance, the ignition system may fail to produce a spark across the electrodes or, if gas ignition is used, to produce a flame. There may be, anywhere between the storage tank and the jet, a stoppage in the oil supply system preventing oil from being ejected from the nozzle. Even if the flame starts initially, a lack of response on the part of a thermostat to detect the change in flue gas temperature may cause the oil pump to stop. Furthermore, during the normal running of the boiler, should the flame fail—possibly through a stoppage in the oil supply—the flue thermostat will act as soon as the flue temperature drops and thus cut off the supply to the oil burner.

CONTROL OF GAS BOILERS

The control of a gas boiler by automatic means presents no difficulties. It is, of course, necessary to protect a gas-fired installation so that gas will not be passed to the main burners unless the pilot jet is alight and it is considered good practice to install a flame failure device to act as a master control.

Control of the gas supply to the main burners is achieved by an immersion thermostat which operates an automatic valve in the main gas line, the control circuit being wired through a switch or other device which, in turn, is controlled by a unit sensitive to the pilot flame. If there is no pilot flame when the controlling thermostat is calling for heat, it will not be possible to complete the electrical circuit to the automatic gas control valve which cannot, therefore, open. Similarly, if the pilot flame is extinguished during normal running of the burner the flame-failure-sensitive device will operate to override the demand of the controlling thermostat and close the main valve to isolate the gas supply from the burner.

Initial starting up of a gas-fired boiler requires manual operation of the switch or safety valve controlled by the flame sensitive device, and as soon as the pilot flame has been satisfactorily established the controlling immersion thermostat can open the main valve; the installation then becomes automatic in operation until the pilot flame should be extinguished either accidentally or intentionally. Operation of the flame-failure device during the normal running of the boiler and the consequent isolation of the main gas supply necessitate the flame failure device being manually reset before the boiler can be lit and it is then necessary to observe certain precautions in the relighting operation—in particular, to be sure that the combustion chamber is properly cleared of gas.

CONTROL OF HAND-FIRED BOILERS

Provided that proper attention is paid to boiler maintenance and to firing, it is possible to control a hand-fired boiler automatically so that the full advantages of general automatic temperature control can be obtained.

For the very small boiler used for small house heating, it is possible to obtain a control unit operated by liquid expansion, movement of a unit immersed in the boiler water being transferred through suitable linkage to a door which controls the primary air supply to the boiler. For the proper functioning of such a control it is essential that all other means of ingress of air be stopped because the slightest leak can completely nullify the control. For this reason it is usual to restrict the application of this type of control to boilers specifically designed for it and provided with a close-fitting primary air door. But it is

also necessary to make sure that all other doors are fitting well and securely shut. All automatically controlled air dampers should be positioned at the back of the boiler where they will be free from interference which might result in their being jammed in the open position.

Hand-fired cast iron sectional boilers for larger installations can be controlled by means of an electric motor linked to the primary air door and a spoil-draught door on the smokehood so arranged that as one is opened the other is closed. The motor used for this method of control should be of the spring return type which opens the primary air door when the controlling thermostat calls for heat, and holds it open electrically until the thermostat is satisfied, whereupon its contacts open, breaking the current, and the motor returns to the starting position with the primary air door closed under the action of the spring. The advantage of this type of motor is that the air supply to the boiler is automatically cut off in the event of a failure of the electricity supply, because the spring, which is compressed during the initial opening movement, remains so only so long as the electricity supply continues. When the supply is interrupted, either intentionally by the thermostat becoming satisfied or accidentally through a supply failure, the motor is returned to the starting position with the primary air door closed and the spoil-draught door open.

CONTROL OF CALORIFIERS

Control of a water/water or a steam/water calorifier consists of varying the flow of the heating medium (primary) to satisfy the demand of the heated medium (secondary), and the instruments used are an automatic valve in the primary operated by an immersion thermostat in the secondary.

VARIABLE TEMPERATURE CONTROL OF SPACE HEATING BOILERS

The rate of total heat input to a space-heating installation is directly proportional to the difference between outside and inside temperatures and the main variable is the outside temperature so that by using this to control the boiler output control of the total rate of heat input may be achieved and in many cases is all that is required.

It is possible to control the calorifier or the appliance firing the boiler by an immersion thermostat whose control temperature is automatically varied by a device sensitive to the outside weather. By this means the temperature of the water flowing to the heating system varies inversely with the outside temperature so that the heat input generally balances the heat requirement in all weather conditions.

This is done by means of a compensating thermostat which consists of three units, (a) the thermostat itself whose stem is immersed in the boiler water,

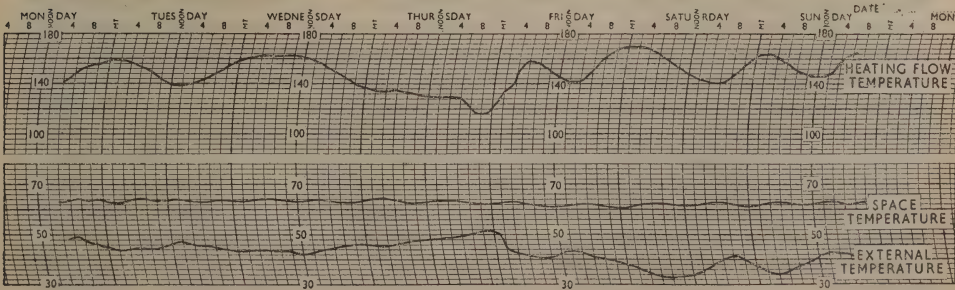


FIG. 2. One-week Thermograph record for thermostatically-controlled boiler installation.

(b) the external weather-sensitive unit, and (c) a balance box which translates the responses of the outside unit to the thermostat. The relationship between outside temperature and boiler temperature can be adjusted to suit the particular installation so that the balance of heat input to heat requirement is maintained generally throughout the normal range of outside temperature during a heating season, which can be 30 degrees F. Fig. 2 is a reproduction of actual records from such an installation, covering a period of one week.

CONTROL OF DUAL PURPOSE BOILER

Direct control of the boiler output by compensating thermostat is not always possible, particularly where the boiler plant has a dual purpose and supplies process or domestic service in addition to space heating. In such cases it would not be acceptable to modulate the temperature of the supply to the hot water service or process since in mild weather it could result in the water temperature being about 110° F., which is too low. Nevertheless, the need to modulate the heating flow water temperature according to the outside temperature is very strong and by the use of a three-port mixing valve it is possible to satisfy the claims of both space heating and other services. Fig. 3 illustrates a system

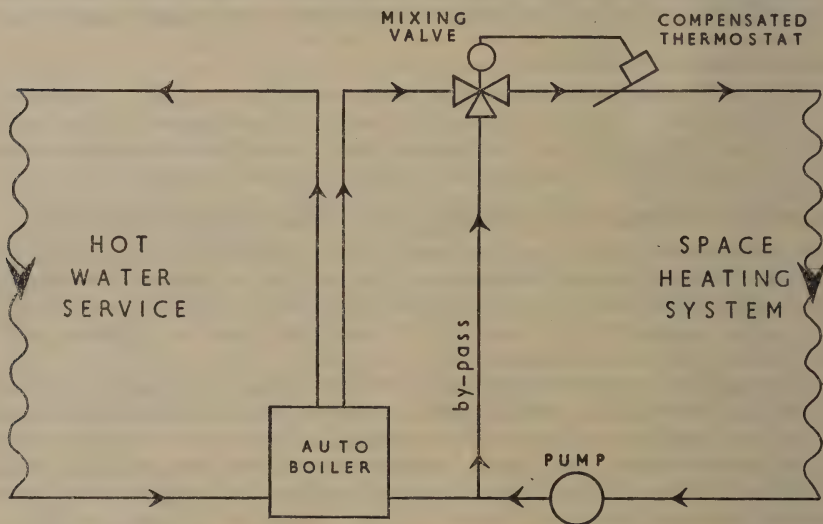


FIG. 3. Application of modulating mixing valve to dual system.

incorporating a three-port modulating mixing valve installed in the heating flow circuit. The third port is connected through a by-pass pipe to the heating return. The mixing valve is controlled by a compensated thermostat immersed in the flow water on the heating system side of the mixing valve so that it regulates the valve so as to modulate the quantities of boiler water and return water to provide the precise temperature required for the heating flow. The boiler control thermostat is of the fixed temperature type set at perhaps 180° F.; the temperature is thus high enough at all times for the other services.

A further instance of control of boiler output directly by modulating thermostat not being desirable in spite of the boiler being used exclusively for space heating, is where there is danger of boiler corrosion because the average temperature in the boiler in mild weather would be lower than the dew point of the flue gas and cause condensation on the boiler walls. In this case also, the boiler can be controlled at a fixed high temperature and the compensated thermostat used to control a mixing valve as before.

In such cases it is necessary to provide a safeguard against excessive boiler temperatures which might develop if the mixing valve is closed and it is usual to provide a small circuit for this purpose. In some cases a by-pass circuit is arranged across the boiler between flow and return so that the average boiler temperature is kept high enough to prevent condensation; when this is done, it is not necessary to use a separate relief circuit because the by-pass will dissipate the excess temperature when the mixing valve is closed.

CONTROL OF MULTI-BOILER INSTALLATIONS

When the installation is big enough to demand two or more boilers feeding a common header, it is usual to link the boilers for control purposes, stopping and starting all the firing appliances together through the agency of a single controlling thermostat in the common header, with a limit thermostat in each boiler to cut off its particular firing device if that boiler temperature becomes too high. The advantages of *linked control* are that each boiler does its fair share of work and, particularly where mechanical stokers are used, there is then no danger of one hopper being emptied while the others remain full.

If modulated flow temperature control is used, the common controlling thermostat would be the compensated type with a maximum setting of, say, 180° F., and the limit thermostats on each boiler would be set to a fixed temperature of 190° F.

During the heating season it may not be necessary to operate all the boilers continuously and this control system permits of automatic selection according to the outside temperature without interfering with the method of water temperature control used. For instance, if three boilers of equal rating are installed for central space heating, whereas they will all be required when the outside temperature is 30°–40° F., two will be sufficient when it is 40°–50° F., and one when it is above 50° F. Selection of the required number can be made automatically by two thermostats installed outside the building, in this particular example one being set at 40° F. and the other at 50° F. If the temperature is below 40° F., the three boilers are brought into circuit, if it is between 40° and 50° F., two are brought in, and if it is above 50° F. only one is brought in. Whatever the number of boilers in circuit, the common compensated control thermostat will continue the work and control the frequency of operation of the firing appliances so that the total heat input and the heat requirement will always be balanced. By a simple manual switching system, the work can be spread equally amongst all boilers by changing the order in which the outside thermostats select them.

The possibility, with such an arrangement, of the idle boiler or boilers acting as radiators can in certain cases be obviated by the use of automatic valves which prevent circulation through the idle boilers. A fully automatic installation such as this would be suitable for oil-fired or gas-fired boilers, but if it were applied to mechanically stoked solid fuel boilers, the idle boilers would have to be maintained on kindling control continuously against a demand for their use. Alternatively, a signal would have to be made when their use was demanded so that the attendant could light the fire.

Selection of one or more boilers in a multi-boiler installation can quite well be done by hand, aided if desired by outside thermostats set to the critical temperatures and arranged to light a lamp or make some other suitable signal in the boiler house, or according to the process requirements as the case may be. This should not be taken to imply that manual control is better than automatic control; the heat output is still controlled automatically whether one or more boilers are on load, and no more heat is produced than is required, but there is some choice in the method of boiler selection.

MODULATING CONTROL OF FIRING APPLIANCES

Except for those mechanical stokers that have automatic thermostatic selection between two alternative rates of coal feed, most automatic boiler firing appliances burning coal, oil or gas, deliver their fuel to the boiler at a fixed rate irrespective of the boiler load, and the thermostat maintains control of the boiler output by regulating the frequency and duration of the feeding impulses so that over a given period of time the heat output and the heat requirement can be balanced.

In an earlier paragraph it is shown that a multi-boiler installation can be controlled so that the quantity of fuel fed at one impulse can be varied by automatically varying the number of boilers in circuit, according to the load, and some work has been done on devising methods of automatic modulation of the rate of fuel feed to single boilers so that the appliance will practically continuously feed fuel at a rate to match the boiler load. For instance, the rate of oil feed from the jet of an automatic oil burner can be varied by using a constant displacement pump and automatically varying the setting of the relief valve controlling the amount of oil fed back into the oil ring main and hence the amount delivered by the jet into the combustion chamber. Alternatively, a variable displacement pump can be used, the automatic control here being applied to the stroke of the pump.

A gas burner can use a modulating valve in the gas supply line to automatically vary the quantity of gas emitted to the main burner, and the gear box of a mechanical stoker of the underfeed or moving grate type can be either infinitely variable or provided with a large number of discrete steps.

Suitable modulating motors and thermostats are already available for many such purposes, but the difficulty lies in their application. If the feed change mechanism is controlled by an immersion thermostat in the boiler water, the action of this thermostat in effecting a change in the rate of fuel feed may be so slow that the feed rate will *hunt* between maximum and minimum, and true modulation with its assumption of a steady rate of fuel feed will not be obtained.

If, however, the feed change mechanism could be controlled directly, as is a compensated thermostat, by a device sensitive to the condition that affects the total demand (such as the outside weather in the case of a space heating installation) it would be possible to modulate the fuel feed rate so that the appliance would operate more or less continuously, with the minimum of hunting, at a rate which would balance the demand.

CONTROL OF STEAM BOILERS

The foregoing remarks on the control of boiler output apply primarily to low pressure hot water boilers, but they are also generally applicable to steam boilers.

A steam boiler feeding a steam heating system is not so flexible as a water boiler for space heating because the output cannot be so readily controlled to balance the outside temperature. But for many space heating installations, for example of the radiator or panel type, the circulating medium is water heated by the steam boiler through a calorifier and the temperature of this water can be modulated by a compensated thermostat controlling the admission of steam to the calorifier.

CONTROL OF SPACE HEATING RADIATOR INSTALLATIONS

Some of the foregoing sections have been devoted to an explanation of the way in which the temperature of the water delivered to a space heating installation can be modulated according to the outside temperature so that, gene-

rally, the mass heat input to the installation is just sufficient to balance the requirement.

That state of balance would exist if there were no variables affecting the space temperature other than changes in the outside weather, but in practice there are differences in the solar heat gain according to the aspect of the building or part of the building and in incidental heat gains due to occupancy or from process work or lighting.

The effect of these variations on the space temperature can be taken into consideration when the heating system is being designed by dividing it into individual circuits for those parts of the building which are likely to be affected by such variations so that the individual circuits can be controlled by automatic motorised valves and room thermostats.

The foregoing applies essentially to those installations where mass control has been imposed on the boiler output so that in general the heat output from the boiler balances the heat requirement and a constant level of temperature throughout those parts of the building not affected by the variations described will be attained. Consequently, whereas the circuits to the parts of the building affected by these variations will have a room thermostat and motor-operated valve superimposed on the mass control, the other parts of the building (fed by the remaining circuits) will be able to maintain a reasonably constant comfort condition. The effects of solar radiation and the orientation of the building can so influence the heat requirement that in some cases it is expedient to divide the main heating circuits into zones and control each by its own compensated thermostat operating a mixing valve, the outside element of each compensating device being positioned so that it is affected by the same weather conditions as affect the part of the building it is controlling. This is termed *zone control*.

Fig. 4 is a diagrammatic lay-out of a space heating installation showing a number of zone and other controlled circuits.

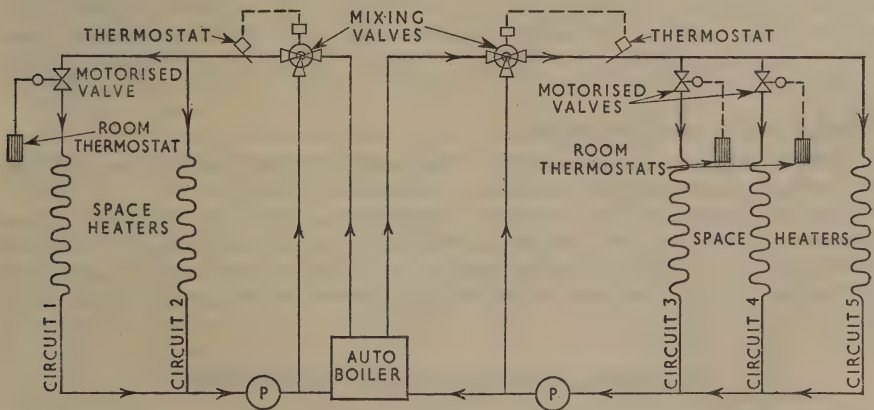


FIG. 4. Zone-controlled space heating.

CONTROL OF PANEL HEATING SYSTEM

Space heating by the use of low temperature embedded panels instead of radiators is quite popular. These panel systems generally use a maximum water temperature of 130° F., which can be automatically varied between 100° and 130° F., according to the outside weather by means of a compensated thermostat acting on a mixing valve.

If it is necessary to make provision for variable occupancy or other incidental heating, the mass temperature control which the compensated thermostat

gives to a panel heating system can be supplemented by the use of room thermostats and motor-operated on/off valves to control the flow of water to the panels.

CONTROL OF PLENUM HEATING

Ducted warm air heating systems use hot water or steam batteries for heating air which is blown over them by means of a fan before being distributed to the space to be heated.

Control of such systems is by means of an automatic valve on the supply of steam or water to the battery and operated either by a thermostat in the duct outlet to maintain a constant outlet air temperature or, preferably, by a room thermostat so that account is taken of the actual requirement of the heated space. Where the heater battery is controlled by the room thermostat it is usual to interpose a low limit duct thermostat which overrides the room thermostat to prevent the issuing air temperature falling so low that it would cause uncomfortably cold draughts.

CONTROL OF MIXED HEATING SYSTEM

It sometimes happens that the heating installation in a particular building is designed to use radiators in some parts of the building, embedded low temperature panels in another part, and plenum in another part, and it is possible to control each of these particular sections in accordance with the methods described in the previous paragraphs.

For instance, the boilers or calorifiers can be controlled at a fixed temperature and the temperature of the heating flow water to the various parts of the building controlled by the use of a mixing valve and a compensated thermostat in each section. In the case of the radiator system the compensated thermostat would operate the mixing valve so that the heating flow temperature varied between 110° and 180° F. approximately, in accordance with the outside temperature, whilst the panel warming circuit would be controlled so that the flow temperature varied between 100° and 130° F., individual space temperatures being controlled in each case by means of room thermostat and motor-operated valves.

CONTROL OF UNIT HEATERS

Space heating by unit heaters is frequently adopted in factories, and the automatic control of these devices presents no difficulty.

The usual method is to stop and start the heater fans by means of room thermostats placed in strategic positions. These thermostats can be of the pattern which includes a built-in short circuiting switch which can be used in summer to allow the fans to run and so promote some air movement in the space.

CONTROL OF AIR CONDITIONING PLANT

The proper control of an air conditioning plant is a little more complicated than that of any of the systems already described since it usually requires control of humidity as well as of temperature.¹

Control of space temperature can be achieved by a room thermostat acting either on the main heater battery or on a booster heater if the plant is provided with a number of outlets with individual heaters, the main heater then being controlled by a duct thermostat to maintain a constant air temperature to the booster heaters.

Humidity can be controlled by controlling the mixture of recirculated and fresh air or by control of the pre-heater or air washer.

The particular method of control of an air conditioning plant depends largely on the type of equipment, but whatever type of plant is installed it can readily be controlled automatically so that it fulfils its proper function of conditioning the air and maintaining it in a constant condition of temperature and humidity despite the wide fluctuations in outside weather conditions throughout the year.

NIGHT CONTROL OF SPACE HEATING INSTALLATION

Many centrally heated buildings are occupied for a comparatively short period. For instance, an office block or school is usually occupied for a little more than a quarter of the total number of hours in a week and it is clearly uneconomical to heat such a building during the unoccupied hours except in so far as is necessary to ensure that it is at the correct temperature during the occupied hours, and particularly at the start of each day, and to prevent the temperature falling so low as to cause damage either to the equipment or to the pipes through freezing.

In theory, any building not occupied throughout the whole day and night could have the heating cut off as soon as the occupants leave and not restored until it is due to be occupied in the morning. In practice, however, although it is possible to cut off the heating an hour before the occupants leave in the evening, it is necessary to bring it on again some hours before opening time in the morning to make sure that it is at the correct temperature for occupation.

The rate at which the building cools down when the heating plant is stopped depends upon the thermal characteristics of the building and on the outside weather, and the rate at which the inside temperature is restored also depends upon these same factors as well as on the capacity of the heating plant.

The most important consideration in night control of a space heating installation is deciding the time that the plant should be started up so that the space temperature will be at the desired level in the morning. It will be seen from the preceding paragraph that the only variable factor affecting the rate of space temperature recovery is the outside weather; it seems logical, therefore, that this factor should be used to determine the starting time of the plant.

By the use of two thermostats placed outside the building and connected electrically to a multi-switch time switch having adjustable time settings, it is possible to set the thermostats and the time switch so that the starting time of the plant is automatically selected according to the weather. For instance, in one typical office block efficient night control is being obtained by stopping the plant at 5 o'clock each evening (the occupants leaving at 6 o'clock) and starting it again at midnight if the outside temperature is 35° F. or below, at 4.00 a.m. if the outside temperature is between 35° and 50° F., and at 7.00 a.m. if the outside temperature is above 50° F. These times have been found suitable for this particular installation, but both thermostat and time switch settings can be altered to suit individual cases.

The length of time for which the heating plant can be stopped during the night depends largely upon the margin which is provided over the maximum design requirement; the smaller the margin the shorter the time that the plant can be isolated, because a longer time is required for restoration of space temperature. It is possible to vary the arrangement during holiday periods and in the case cited above, where the margin of the heating plant is not more than 10 per cent. over the maximum design requirement, it has been found that the space temperature does not fall unduly and can be restored by Monday morning if it is left off completely during Saturday and started again on Sunday morning. For a recent holiday period of five days it was found that the plant could be shut off completely for the first, second and fourth

days of the shut-down, being run during the daytime only on the third and fifth days.

The graph in Fig. 5 shows the variations in the space temperature during this holiday period, the on/off times being marked. The building is of conventional brick construction.

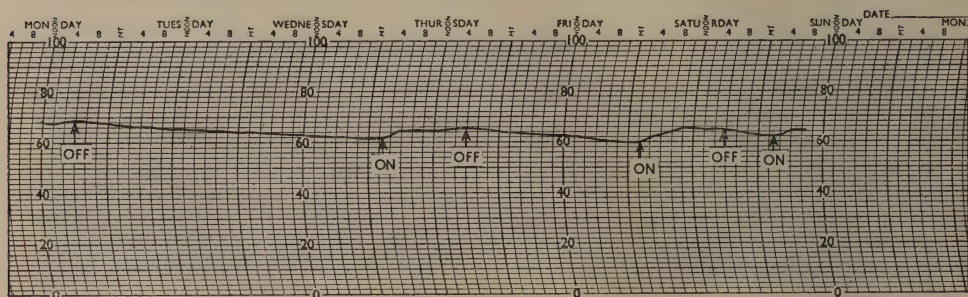


FIG. 5. Five-day holiday period thermograph recorded during factory "shut-down".

CONTROL OF PROCESS HEATING INSTALLATION

The control of the mass heat input for the various processes being carried out in a particular factory can be effected by a thermostat or steam pressure actuated switch controlling the boiler output and although this is not sufficient to afford control of each individual process it is the first stage in solving the problem and ensures that the boiler output is not excessive.

The method of controlling the distribution of heat to the individual process depends largely upon the nature of the process being carried out, but it usually resolves itself into the installation of a thermostatic system sensitive to air, liquid or platen temperature.

The control of air temperature in, for instance, an oven with built-in heaters or a drying room with the heat supplied by warm air entering through ducts or grills, can be achieved by a thermostat sensitive to the air temperature and connected to an automatic valve so that the supply of heat is regulated according to the demand.

For the control of liquid temperature in dyeing vats, electroplating baths and similar installations, an immersion thermostat sensitive to the temperature of the liquid can be used to control the flow of heat to the vat or tank, by means of an automatic valve used to regulate the flow of steam or high pressure hot water.

Where quick heating is required, the correct size of control valve for maintaining the liquid at boiling point will probably be too small to supply the steam or high-pressure hot water at the rate necessary for heating-up. This can be overcome by supplying the thermostatic valve in a by-pass of reduced size, around the hand valve in the main supply, and using the hand valve for heating up. When boiling point is reached the hand valve should be closed and the thermostat be allowed to take over the control (see Fig. 6).

The following example illustrates the waste that can occur on process plant. A thousand gallons of water contained in a closed vessel have to be brought to boiling point in one hour and kept at that temperature for several hours. The factors involved are as follows:

- (a) *Heating-up.* Heat required to raise 10,000 lb. (1,000 gal.) of water through 160 deg. F.=1,600,000 B.t.u. (excluding heat losses).

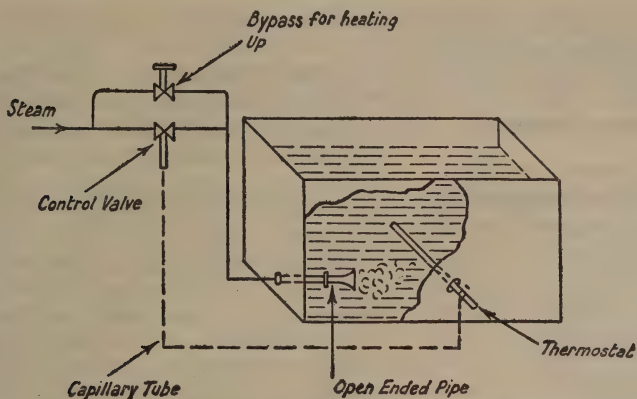


FIG. 6. Thermostatic control of process heating.

- (b) *Maintaining temperature.* Surface area of vessel exposed to atmosphere = 70 sq. ft.

Difference of temperature between vessel and atmosphere = 150 deg. F.

Heat losses = 2 B.t.u./sq. ft. hr. deg. F. (see Chapter 9).

$$= 2 \times 70 \times 150 = 21,000 \text{ B.t.u. per hour.}$$

The heat required per hour to maintain the temperature is thus only 2 per cent. of that required for heating-up. Unless the supply is promptly checked when the required temperature is reached, 98 per cent. of the heat in the steam will be wasted as long as it is allowed to remain full on.

In this example no account is taken of the additional losses by evaporation from the open surface of the liquid; but this would not materially affect the great disparity between the steam requirements for heating-up and for keeping up the temperature. With manual control, of course, the steam valve would be throttled down by hand, but it would be practically impossible to throttle down by just the right amount—waste is inevitable.

Platens can be maintained at a steady temperature by the use of a stem type thermostat inserted in the platen and controlling the heating medium.

TYPES OF THERMOSTATIC CONTROL

IMMERSION THERMOSTATS

Immersion thermostats of the stem type are usually of either the bi-metallic strip or liquid expansion type and consist essentially of a thermally-operated electric switch which can be applied according to the nature of operation of the device it is required to control. Where compressed air is used to operate control systems, thermostats are of the air leak pattern.

Immersion thermostats for temperature control of liquids can be supplied with pockets or sheaths in a wide range of different materials suitable for use with various corrosive liquids—a necessary feature in process work.

PRESSURESTATS

On the smaller type of industrial steam raising plant the boiler thermostat used for hot water boilers is replaced by a *pressurestat* which is sensitive to pressure instead of to temperature (see Fig. 7). This instrument comprises a bellows or flexible diaphragm on which the pressure operates, linked mechanically to an electric switch and opposed by a spring. The spring tension is adjustable so that the switch can be made to operate at the desired boiler pressure. The pressurestat controls the electric supply to the motorized damper gear in a natural draught gravity-feed or hand-fired boiler, or to the stoker motor on

a mechanically fired boiler. A boiler level control is a further useful aid to economical boiler operation.

Larger boiler plant requires more elaborate equipment, there being several systems available, but the basic principle remains broadly the same, except that the auxiliary operating power may be hydraulic or pneumatic instead of electric.

PRESSURE CONTROL

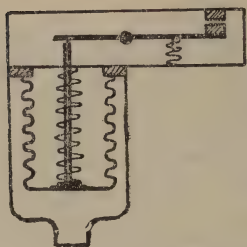


FIG. 7. Control of steam boilers.

A note of warning may be sounded here to the effect that while boiler control systems will regulate the draught in accordance with the load, they cannot influence the management of the boiler in other directions. It is still necessary for the attendant to see that his fire is in good order, containing no holes or thin places, for the plant to be maintained in good order, and so forth.

AIR THERMOSTATS

Thermostats for the control of air temperature in duct or oven are usually similar and, like the immersion thermostats for liquid temperature control, are of either bi-metallic strip or liquid expansion type.

Air thermostats for temperature control are usually of either the bi-metallic strip or vapour pressure type and are designed for fixing to the wall in the space when temperature is being controlled.

AUTOMATIC VALVES

Automatic valves for control of the flow of liquids or gases under the action of a thermostat can be of the solenoid, electric motor, hydraulic or pneumatic operated type. The choice depends largely upon the type of control system used but the valve bodies are substantially the same.

For the control of hot water flow to a space-heating installation, an on/off butterfly valve is normally used, operated by a small electric motor fixed to the valve body. For the control of high pressure hot water, particularly for process heating and for space or process heating calorifiers, the valve must be able to withstand the more arduous conditions imposed by high pressure hot water. The valve may be of either the on/off or modulating type. For the control of steam flow, the valve may be of either the on/off or modulating type, depending upon the installation.

Modulating valves for the control of water or steam are intended to restrict the flow through the pipe so that the load requirement is satisfied in all conditions and the heat input is continuous, being changed, increased or decreased, by a suitable controlling thermostat. The application of modulating valves, for the control of steam or water flow, demands a good deal of thought if the valve is to modulate properly throughout the whole of its operating range, and it is necessary to size the pipe correctly according to the service required.

The range of controls available is considerable, extending as it does to all types of thermostats, thermostatic controllers and automatic valves operated electrically, pneumatically or hydraulically and arranged to give on/off control for the simplest installations or modulating control for the more complicated ones.

ELECTRONIC CONTROL

In recent years there has been an increase in the use of electronic devices

for meeting problems of control in a wide variety of fields. The control of temperature is a specially suitable field for its application. As an example, an exceedingly sensitive temperature controller can be constructed by using an electrical resistance rapidly responsive to small temperature changes. This is linked through a thermionic (electronic) amplifier to the motor actuating the control valve or valves of the system.

INSTALLATION AND MAINTENANCE OF THERMOSTATIC EQUIPMENT

The most useful advice that can be given concerning the installation of thermostatic control is that the makers recommendations should be followed.

In the installation of the temperature-sensitive devices, e.g. immersion thermostats and air thermostats, commonsense must be the main guide. The thermostat must, of course, be installed where it will be sensitive to the conditions in the space or process being controlled and it must not be installed where it is likely to receive mechanical damage or where it will be influenced by local factors that do not influence the process or space as a whole.

Maintenance is essential for the successful operation of all instruments. Since thermostats are responsive to very small changes of temperature, they must be handled with the care due to a sensitive instrument and efficiently maintained.

The following instructions for the maintenance of control instruments are extracted from Fuel Efficiency Bulletin No. 11.

Thermostats. Immersion thermostats should be checked for leaks at the point of immersion; the continual expansion of the apparatus into which they are placed may cause the holding nuts to loosen.

The thermostat should be removed from time to time for inspection for corrosion and deposit. If deposits are allowed to accumulate they may act as insulation and make the action sluggish. Terminals should be kept clean and tight. Covers should always be in place and the position of the scale pointer should be checked.

An occasional check should be made to ensure that the thermal action of the thermostat is correct; no unauthorized person should tamper with the settings.

Thermostats should never be oiled.

Dampers and Damper Operating Motors. Maintenance of damper linkage is most important, and should be carried out at regular and frequent intervals. The motor links are disconnected and the dampers and their linkage operated by hand. Any stiffness should be immediately rectified, particular care being given to the bearings of primary and secondary air dampers.

Motors should be checked in the usual way. They should in general require no lubrication, since they are sealed and the moving parts are immersed in oil.

When the damper motor is in the "fully open" position, the damper must be checked to ensure that it, too, is fully open. When a check damper is fitted care must be taken to ensure that it opens properly when the main damper closes.

Motorized Valves. These must be examined for dirt and loose connections in the terminal box and the motor insulation must be tested. The valve gland should be examined for traces of leakage. On certain types the gland nut should on no account be tightened. The makers' instructions should be followed regarding lubrication; in general, lubrication would only be applied if points are provided.

Relays. The interior should be kept clean and examined for loose connections. It is necessary to make sure that the armature can be freely closed by hand, and that it has no tendency to stick in the "closed" position. It is very rarely necessary to clean the contacts; on certain types of relay this may be

actually harmful.

If the relay has become noisy after a period of service, the pole faces of the electromagnet should be cleaned. To do this, a clean piece of paper is placed between the pole faces, the armature is pressed down firmly with the fingers and the paper is withdrawn whilst maintaining the pressure. Usually the armature pivot does not require lubrication, but when lubrication is desirable, oil should be used very sparingly.

Covers should always be in position.

Humidity Controls. Hair elements should be washed with a camel's-hair brush and clean ether; wetting with distilled water will moisten the hair element to its original sensitivity.

Compensated Control Systems. This type of control system as well as any other more complicated controls must be carefully checked for accuracy at all primary and secondary control points. A differential inaccuracy at any point in a line of controls may throw the whole system out of adjustment.

Differential Adjustments. It may be found that the number of operations in the plant are too many; this may be reduced by increasing the operating differential. The operating differential should be as narrow as possible and brought to a point consistent with the heat distribution requirements. This also applies to pressurestats operating stokers, motorized valves, dampers, etc.

Differential adjustments should be checked for cut-in and cut-out against the flow thermometer and/or pressure gauge. The cut-in pressure or temperature plus the differential equals the cut-out pressure or temperature.

Low Water Controls. The blow-down valve should be opened daily and the float chamber should be opened occasionally in order to remove any sludge that has accumulated. Switch connections should be checked for dirt, etc.

Control Valves. Where the controlling device is a valve, it should be protected against foreign matter by a pipe line strainer which should be cleaned periodically as may be found necessary. The valve itself should be examined to see that the seatings are clean and not wire drawn, and that its movement is free.

Repairs. Where a control is beyond ordinary maintenance it should be removed and sent to the makers for repairs. Thermostatic controls are highly specialised instruments and major repairs should only be carried out by qualified mechanics.

Alarm Controls. Where failure of a thermostat would have serious consequences, an alarm to give a visible or audible warning that a dangerous temperature is being approached is recommended.

A test switch is advisable in such alarm circuits, or in connection with automatic safety devices which are only called upon to operate in emergency. A test should be made regularly by this means to make sure that the circuit is intact and operates correctly.

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CHAPTER 29

SAMPLING OF FUELS

INTRODUCTION

ALMOST all analytical procedures relating to the fuels commonly used in industry have been studied and prescribed in much detail, and can be performed with great accuracy. Less attention is paid to the technique of obtaining for analysis a sample that shall be representative; methods of sampling have been worked out with greater or less completeness, but necessary details in the procedures are often tiresome to carry out and are sometimes only perfunctorily observed. It is clearly unsound to do an analysis with a higher order of accuracy than that with which the sample has been taken. For this reason it is imperative to secure adequate representativeness in a sample by choosing a method of sampling adapted to the conditions prevailing, and carrying it out punctiliously.

As a low standard of accuracy in sampling completely vitiates the work of the most competent and careful analyst and nullifies the reliability of any heat balance or calculation of thermal efficiency, this is an appropriate place in this book to refer to the general subject of Standards of Accuracy. In the treatment, in Chapters 9 and 10, of theories of heat transmission and fluid flow many mathematical concepts have been discussed. These have involved formulae, expressions and equations implying high degrees of accuracy, some justified on well established laws, others based on experimental work following upon their application in practice. But the engineer applying these principles and formulae, especially in constructing heat balances, must guard against straining unduly to attain what would be a misleading degree of accuracy. The accuracy attained in the use of formulae, no matter how accurate in themselves, depends upon the precision of the instruments or equipment used in applying them.

Accordingly, although examples worked out in Chapters 9 and 10 suggest the possibility of reaching a high degree of accuracy, extending beyond (say) four significant figures, that is unavoidable in the development of the argument and in illustration of the principles involved. Similarly, in making boiler trials and constructing heat balances, discussed in Chapter 26, a great deal of common sense must be applied when working out results and tabulating them. The degrees of accuracy represented by these data must obviously vary widely, and tabulating them is a task beset with pitfalls and leading to misleading impressions of accuracy. To express a boiler efficiency as (say) 72.74 per cent. is an example in illustration. Such a figure must incorporate some data accurate to perhaps only one place of decimals or even to the nearest whole number; other components of the total may, on the other hand, be accurate to the second place of decimals (or even the third). But the sum total, quoted above as 72.74, must obviously be rounded off to (say) 72.5. When a whole number result is wanted, the decision to round up or down may depend in practice on the purpose for which the figures are required, and on the errors inherent in the determination.

Arguments in which the effects of several variables are compound should not be obscured by the inclusion of items of widely different magnitude. If the performances of several ancillaries are being compared it will be necessary to record the data relating to them. That does not necessarily imply the ultimate inclusion of these data in a grand total in such a manner as to violate the principle just expressed.

Similarly, if in a heat balance resulting from a boiler trial a total of (say) over 2 million B.t.u. is obtained, there may be many small items each in itself quite accurate; but their individual effects may be quite overshadowed by their inclusion along with other items some of which may total many hundreds or even thousands, accurate only to 3 or 4 significant figures. The accuracy may, so to speak, terminate in the units or tens or hundreds column. The operator has probably no alternative to summing up the items as tabulated, but he must obviously round off the final result rigorously and thus obtain a total which by itself may be correct to only four significant figures (not places of decimals) according to the influence of the largest items.

SAMPLING OF SOLID FUELS

There are two main reasons for sampling a solid fuel. In the first place, the price of the fuel is, or should be, determined largely by its quality: to apply and understand any coal price structure, it is essential to have reliable information regarding the amount of worthless material present in the fuel, and the character, in particular the calorific value, of the pure fuel. Secondly, in order to carry out acceptance tests and to ensure the efficient running of boiler installations and other industrial plant it is necessary to know with some precision the amount of heat going into the plant in order that reliable heat balances (Chap. 26) may be drawn up.

The tests applied in assessing coal quality are mainly chemical analyses. These analyses are made on relatively small quantities of finely powdered coal. For instance, the standard method of ash determination is to incinerate 1 g. of coal ground to pass through a sieve of aperture size 0.008 in., this quantity of 1 g. usually being taken from a bottle containing $\frac{1}{2}$ lb. (227 g.) of coal (see Chap. 30). However, if only $\frac{1}{2}$ lb. of coal were taken out of a whole consignment it could hardly be considered to be representative of (say) a 100-ton consignment; it would be equivalent to not more than two or three pieces of 2 in. coal and only a fraction of a typical lump of house coal.

This means that it is necessary to take, in the first instance, a much larger quantity of coal than is required for the actual testing in the laboratory. Consequently, to obtain a reliable figure for the quality of a consignment of coal, it is necessary to carry out three separate processes, each one with specified accuracy and without bias. These three stages are:

- (i) obtaining a gross sample from the whole consignment,
- (ii) treating this gross sample so as to obtain a quantity of finely ground coal representative of the whole consignment, for use in the analytical laboratory.
- (iii) chemical analysis of quantities of the order of 1 g. taken from the laboratory sample.

An inherent difficulty in judging the accuracy of sampling of solid fuel lies in the fact that the "true value" for a consignment is never known, so accuracy has to be assessed from a comparison of several samples. But care has to be taken in this because if the sampling is biased (for example, always tending to give a high figure) all samples taken in the same manner will be similarly biased, and a comparison of such samples may give a misleading impression of accuracy. Despite these difficulties it must be accepted (a) that sampling is of fundamental importance and (b) that unless an accurate *assessment of the sampling accuracy* can be made there can be little progress in achieving that reliability in the actual sampling that is essential for the efficient use of solid fuel. It is often considered that accurate analytical work is required in determining the properties of the solid fuel. That is undoubtedly true, nevertheless, if the sampling itself is not of sufficient accuracy no amount of

skill on the part of the analyst will get the right answer.

Much of the complexity of sampling lies in the varied conditions under which it must be done. Thus, a typical Area of the National Coal Board may be faced with the problem of sampling a hundred grades of coal from a dozen or more collieries. This problem of sampling a continuous output of coal is very different from the problem facing the consumer. He is concerned both with keeping a check on the quality of each grade that comes in—usually in consignments of from 100 to 1,000 tons—and with keeping a record of the input to his furnace, for the purpose of drawing up regular heat balances. The acceptance test of a new boiler is only one problem out of many involving reliable sampling procedure. It can be seen that the methods of sampling to be used and the frequency with which sampling is done will depend not only on the site of the sampling but also on the use to which the figures are to be put, and on whether the coal to be sampled is a single consignment or a continuous supply.

A great deal of work done in the past on theories of coal sampling has been aimed at calculating the weight of sample that has to be collected from a given consignment in order to obtain an analysis of specified accuracy. More recently a new approach to the problem, which may be called a statistical approach, has been adopted. This approach starts from the now commonly accepted principles of *statistical sampling*, and then builds up from these on the basis of experimental work. In this way very few assumptions have to be made and the subject of coal sampling is largely being brought into line with experience on the sampling of other materials.

The section on Sampling in the First Edition of this book was based on the British Standard on the Sampling of Coal, B.S.1017¹. That standard was based largely on empirical evidence available at that time (1942) and its reliability has, on the whole, been remarkably vindicated by more recent advances. The standard has, however, been under revision for a number of years, and it is expected that a revised British Standard on Coal Sampling will be issued in 1958. Until the new standard is issued, it is not possible to say in detail what the prescribed methods will be, but an indication of some of the changes that will be introduced has been given in two papers written by members of the Revising Committee^{2,3}. From these papers it appears that the new standard will depart drastically from the old one in one respect: it will devote particular attention to the problem of sampling a coal which is regularly being handled at the sampling point, and on the use of simple statistical techniques of checking the sampling accuracy.

To this end, the technique known as *duplicate sampling*—whereby a sample is taken in two parts which are then compared—will be extensively applied. Much more emphasis will also be laid on the need for care in the reduction of the *gross sample*, i.e. in obtaining the bottle of finely ground coal required by the analyst. Experimental work has shown that unless suitable precautions are taken the errors in sample preparation can be high. Certain other changes will be introduced with regard to the accuracy required and the amount of sample to be taken, but in general the methods of collecting the sample prescribed in B.S. 1017 : 1942 may still be relied on with reasonable confidence.

It is not possible to provide within the space of one short chapter all the information on coal sampling that will be incorporated in a lengthy British Standard, even if all the necessary information were available at the time of writing. All that can be done for the present, therefore, is to outline the principles on which good sampling practice is based, and refer the reader to the appropriate sampling standards for further detail. At the time of writing (1957) the following are appropriate :

B.S. 1017: 1942 Sampling of Coal and Coke

B.S. 1293: 1946 Sampling of Coal for Size Analysis

B.S. 2074: 1954 Sampling of Coke for Size Analysis.

B.S. 1293 is also likely to be revised in the course of the next few years.
B.S. 2074 already incorporates some of the new ideas.

GENERAL PROCEDURES

The general procedure of sampling is to collect a number of small portions, called increments, each increment consisting of the amount of coal collected in one movement of the sampling instrument. The accuracy is affected by the number of increments taken, the weight of the individual increments and the manner of collection. It is essential, in order to get unbiased results, that the increments be above a specified minimum weight. This minimum weight for coals up to 3 in. in top size is generally taken to follow the relationship :
$$\text{weight (in pounds)} = 2 \times \text{size (in inches)}.$$

However, in order to ensure that particles of all sizes stand a fair chance of being included in the increment, larger increments than this will often be needed.

If samples are being taken from the coal as it falls in a rapidly moving stream, a representative increment can be taken from a full cross-section of the stream only by using a container with an opening at least $2\frac{1}{2}$ times the maximum size of the coal. In such cases the minimum size of increment may be very much larger than would be given by the above relationship. Provided, however, that the increment is above the minimum size and is not much too large, the accuracy of the sampling will be determined primarily by the *number* of increments taken. Any adjustment in the accuracy required is allowed for in adjusting the number of increments taken, and not by any other change in the sampling procedure.

Although the methods of sampling are similar whatever property of the coal is under investigation, the subsequent treatment of the samples will vary. Thus, when samples are taken for *screen analysis* the gross sample must be retained in its original form without breakage, screening being carried out, of course, on the whole (uncrushed) sample. If a sample is taken in order to determine the *total moisture* in the consignment, special precautions are necessary in order to ensure that no moisture is lost from the sample in the course of handling. When the sample is taken in order to determine the *ash and other properties* of a coal, other special precautions are required.

In the following sections, therefore, Sampling for Ash and General Analysis, Sampling for Moisture, Sampling Coal for Screen Analysis and Sampling of Coke are considered separately.

SAMPLING FOR ASH AND GENERAL ANALYSIS

A. Sampling from Conveyor Belts and Falling Streams

A sample is taken by means of increments spaced evenly over the whole consignment of coal to be sampled. Each increment should preferably consist of a complete cross-section of the stream. When sampling coal from the falling stream, the sampling instrument should have an opening whose width is at least two-and-a-half times the top size of the coal to be sampled. When sampling from the conveyor belt particular care must be taken to ensure that the full depth of coal is sampled. If it is not possible to cover the whole of the cross section of the stream in a single sweep of the sampling instrument, the number of increments taken from different parts of the stream should be proportional to the mass flow in the different parts. If a scoop or shovel is used it should be of sufficient size and have built-up sides so that it will be able to catch and retain the largest particles.

If each increment is from a full cross-section of the stream, the weight of increment will be determined by the method of sampling. If samples are taken only from part of the stream, the weight should not be less than that given in the following table:

Top size of coal (in.)	$\frac{1}{2}$	1	2	3
Minimum weight of increment (lb.)	1	2	4	6

The sampling of coal with top size of more than 3 inches from a moving stream is a matter of considerable difficulty and should be avoided whenever possible. If the conveyor can be stopped a sample may be taken by clearing a cross-section of the belt, or a sample may be taken from the falling stream by the use of specially supported containers. The increments will in general be very large and it may be convenient to reduce the size of increment to 10 lb. before adding it to the general sample.

The number of increments required depends on the standard of accuracy required. B.S. 1017 : 1942 gives the following numbers of increments for small coal in order to obtain an accuracy of ± 1 per cent. :

<i>Ash per cent.</i>	0-6	6-10	10-15	15-20
No. of increments	11	24	42	65

The number of increments given in this table has generally been found to be satisfactory for most coals, but with some untreated smalls the number of increments prescribed must be doubled.

When the sample has been collected it should be placed in a sack or closed bin in a position protected from the weather until such time as it can be handled in the laboratory. If the sample is to be used for moisture determination as well as ash and general analysis, additional precautions are required to prevent evaporation from it.

B. Sampling from Wagons and Stock Piles

Sampling from wagons and stock piles is generally unsatisfactory since the whole of the coal is not accessible to the sampler. The fundamental condition for unbiased sampling, i.e. that increments should be spaced evenly over the consignment, cannot be complied with. For this reason sampling from wagons and stock piles should be avoided whenever possible, and the sample should be taken in the course of loading or unloading.

It is doubtful if any satisfactory sample can be obtained from a single wagon-load of coal or from any small number of wagons, but when several wagons are to be sampled, an answer to within ± 2 per cent. of the true ash content will generally be obtained by the following method. Coal is removed from selected surface positions on each wagon and an increment taken from about 18 in. below the surface. It is generally desirable that at least 48 increments should be collected and the positions should be varied from wagon to wagon. It should be noted that if a sample is required for determination of moisture it must be taken from the bottom of holes penetrating to half the depth of the wagon.

Sampling from stock piles more than 3 feet high is virtually impossible without the risk of incurring bias. For stock piles smaller than this, a satisfactory sample may be taken by digging into the pile and taking increments from selected points over the pile.

C. Treatment of Gross Sample

The general practice is to crush the gross sample in three stages, each of the first two stages being followed by a reduction in weight. A satisfactory procedure is as follows:

- (i) Crush all the gross sample to smaller than $\frac{3}{16}$ in. or $\frac{1}{8}$ in. ;
- (ii) Sub-divide the sample by a mechanical sampling divider or riffle until a 12-lb. sub-sample is obtained;
- (iii) Crush the 12-lb. sub-sample to pass completely a 25-mesh B.S. test sieve;
- (iv) Sub-divide the 12-lb. to $\frac{1}{2}$ lb., using a mechanical sample divider ;
- (v) Crush the $\frac{1}{2}$ -lb. sample to pass a 72-mesh B.S. sieve.

Precautions must be taken to ensure that there is no unwanted loss of coal in the course of the reduction process, and that the crushers used will not contaminate the sample. The subdivision must be done with great care, as serious errors may be introduced at this point. Hand methods such as coning and quartering are unsatisfactory. A riffle may be used at the first stage of reduction (see Fig. 1), but mechanical methods are desirable for the second stage of reduction.

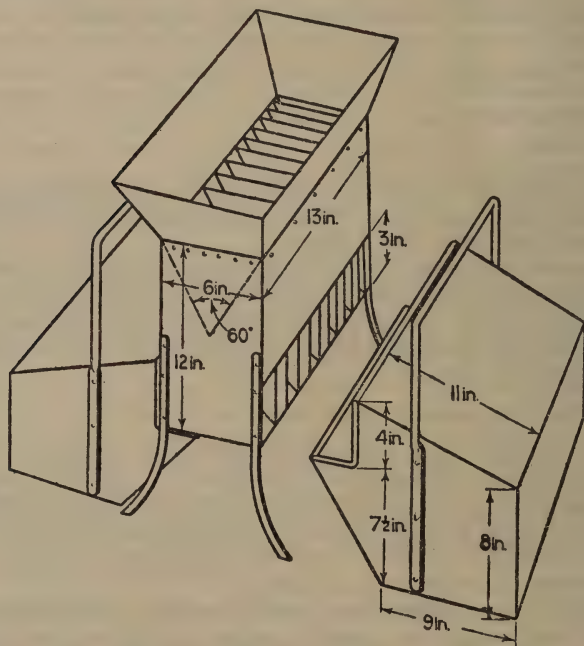


FIG. 1. Riffle sample divider.

Suitable types of mechanical sample divider have been described in Refs. 1, 3 and 4.

SAMPLING FOR THE DETERMINATION OF TOTAL MOISTURE

The moisture content of coal is likely to be changed—generally reduced—both by exposure to the atmosphere and during breaking for reduction in size. Samples for determination of moisture must be collected in containers that can be closed with tightly fitting lids. If the sample is taken solely for moisture determination, ten increments spaced evenly over the consignment should be collected directly into a container. If the sample is to be used for

general analysis also, it is collected as previously described, but directly into the container, and a separate sample for the moisture determination is taken from this bulk, without deliberate breakage, in ten increments spread evenly over the whole.

In general it is preferable to air-dry the whole of the moisture sample and determine the free moisture present as the percentage loss in weight. Care must be taken, however, to avoid over-drying, which may result in a subsequent pick up of moisture. The air-dried sample may then be crushed to $\frac{1}{2}$ in. and a 2-lb. sub-sample extracted. The moisture may be either determined directly on this 2-lb. sub-sample or it may be crushed in a slow-speed mill so as to pass a 6-mesh B.S. test sieve before a $\frac{1}{2}$ lb. sample is removed for analysis. The moisture sample handed to the laboratory should be clearly labelled indicating the percentage of free moisture present in the coal before air-drying.

SAMPLING FOR SCREEN ANALYSIS

The general principles of sampling for ash and general analysis are applicable to sampling for screen analysis. The only differences occur in the number of increments required, and in the particular care that is necessary to ensure that no breakage of the coal occurs in the course of sampling. The recommended number and weight of increments (taken from B.S. 1293 : 1946) are as follows:

Top size of coal (in.)	3-4	2 $\frac{1}{2}$	2	1 $\frac{1}{2}$	1	$\frac{1}{2}$
Minimum number of increments ..	50	50	40	25	25	25
Minimum wt. of increments (lb.) ..	10	6	4	3	2	2

The method of screening the coal is as follows:

Coal containing material larger than 1 $\frac{1}{2}$ in. The coal is placed at one end of the stationary horizontal or inclined screen having 1 $\frac{1}{2}$ in. square openings, and is moved by hand or brushed across the screen until no more passes through, after which each piece is tried by hand to see if it will pass through in any position. The pieces must on no account be forced through the openings. Doubtful pieces are left on the screen. The over-size is then re-screened by the above method, starting with the largest screen or gauge ring.

The under-size is treated as described in the next paragraph.

Coal smaller than 1 $\frac{1}{2}$ in. The coal is placed on screens which are shaken in the following manner :

The screens are moved horizontally at just sufficient rate to cause the pieces of coal to tumble or roll on the screen. The motion is not stopped by impact, and is continued for eight movements (four in each direction). The screens are then given two upward jerks. This is repeated four times, making forty movements in all. The screening is started with the largest screen.

Mechanical screens may also be used provided they are of a type which minimise breakage. A recommended type of mechanical screen is given in B.S. 1293.

SAMPLING OF COKE

Although the general principles of sampling are the same for coal and coke, the physical properties of the two materials are sufficiently different to require separate specifications. B.S. 1017 : 1942 has separate chapters on the sampling of coal and the sampling of coke; the revised B.S. 1017 will be issued in separate parts. [The draft revised standard for the sampling of

coke was issued for comment by industry in November, 1956.^{4]} Methods for sampling blast furnace coke have been described in detail in a specification produced by the Joint Coke Consultative Committee of the British Coking Industry Association, the Council of Iron Producers and the British Iron and Steel Federation. The methods outlined in this section are based on the draft British standard already mentioned. This draft, though not yet having the force of a British standard, may nevertheless be taken to indicate the general consensus of expert opinion at the time of writing.

The two main features which determine the procedures necessary for the satisfactory sampling of a consignment of coke are :

- (1) The greatest variable is generally the moisture content, which varies considerably with particle size.
- (2) Coke is hard and abrasive and does not flow well.

The latter feature makes it particularly difficult to collect a sample fully representative of all sizes of particle; because of the first feature mentioned a bias in sizing is usually reflected as a bias in the moisture content. It should also be noted that coke is generally received by a consumer on a regular delivery basis so that the new procedures for the sampling of regular consignments, notably the technique of *duplicate sampling*, are commonly applicable. The details of these methods are, however, too lengthy to be reproduced here, and reference should be made to the draft British standard and to the actual Standard when published.

For the sampling of isolated consignments, the following four classes of coke are considered:

- Class 1. Large or graded *gas cokes* from which breeze has been removed;
- Class 2. Large or graded *oven cokes* from which breeze has been removed;
- Class 3. *Gas or oven cokes* from which breeze has not been removed;
- Class 4. *Breeze*.

The number of increments required depends on the class of the coke and on the moisture content as given in the following table:

Class	Moisture less than 5 per cent.	Moisture over 5 per cent.
1	36	48
2	72	196
3	144	220
4	18	18

The minimum weight of increment is determined by the top size of coke as follows:

Top size of coke (in.)	.. ..	1½	3	4	over 4
Size of increment (lb.)	.. ..	2½	5	10	15

The quantity of coke to be handled in a single crushing operation should not exceed 150 lb., so that if greater samples than those are required they should be treated as a number of sub-samples, each sub-sample being crushed and analysed separately.

Sampling from wagon tops for ash and moisture is not permissible, though in some cases the sampling from the sloping surfaces of coke in partly emptied wagons may be satisfactory, provided that sufficient wagons are sampled.

The method of sample preparation to be used depends in part upon the sampling equipment available. In the recommended method the gross sample

should first be crushed in a jaw granulator with replaceable manganese steel or chilled cast iron jaws, a 2-lb. moisture sample should then be taken, preferably by use of a mechanical sample divider. A further 2 lb. should be taken for the general analysis sample, and this may be crushed in successive passes through chrome steel crushing rolls, until all passes through a 72-mesh B.S. sieve. The 2-lb. sample should then be reduced in weight to about 2 oz. by means of a suitable mechanical sample divider.

CHECKING THE SAMPLING ACCURACY

The sampling accuracy (whether for coal or coke) may be estimated by the method of *replicate sampling*. If the accuracy of a single sample is required it is necessary to collect at least six sub-samples by placing successive increments into different containers, the same total number of increments being taken as in normal practice. Each of these sub-samples is then analysed separately, and a comparison of the results can be used to provide an estimate of the sample as a whole. A more useful method of measuring accuracy which can be used when the same grade of fuel is being sampled over a period, is to collect each sample in duplicate, i.e. by putting alternate increments into different containers. The two sub-samples so obtained are then prepared and analysed separately, and the results examined after ten samples have been taken in this way. Methods of handling the results of duplicate sampling have been described in References 3 and 4 and in B.S. 2074.

SAMPLING OF LIQUID FUELS

The taking of representative samples from liquid fuels in bulk for subsequent laboratory examination or for reference purposes is an operation of basic importance requiring skill, judgment and experience. Space permits only a brief description of the procedure and apparatus in general use; for fuller details of the most suitable procedure for the different kinds of oil fuels, of the equipment used in sampling and of essential precautions for safety and accuracy, reference should be made to "Standard Methods for Testing Petroleum," published by the Institute of Petroleum⁵.

Every effort must be made to ensure that the sample is as closely representative as possible of the total contents of the main container. If the latter is relatively small (up to 10 gallons) it should be vigorously agitated before the sample is taken. If it exceeds this volume, as will usually be the case, it is customary to take "top, middle and bottom samples" at points one-sixth, one-half and five-sixths of the depth of the liquid below the surface, and to bulk these three samples to obtain an "average sample". Unless there are specific reasons for so doing, samples should not be taken from the bottom of the container where water, rust and sludge are liable to accumulate. Whenever possible they should be taken by dipping (see below) and not drawn from pet-cocks or gauge-glass fittings. If there is reason to expect non-homogeneity in the bulk of liquid, or if dipping is not practicable, the sampler must use his judgment as to the best method of obtaining a representative sample and he should record full details of the procedure employed.

Samples are usually taken by means of a corked sampling can or bottle, of one to two pints capacity. This is mounted in a weighted cage so equipped that the cork can be withdrawn by jerking a string when the can has been lowered to the appropriate level in the liquid. Details of sampling vessels are given in "Standard Methods for Testing Petroleum and its Products".

The bulked "average sample" is then divided among two or more sample cans or bottles, according to the purpose of the sampling operation and the nature and scope of the tests required.

The minimum should be either a one-pint or a 16-oz. sample for testing and a duplicate sample for reference purposes, or in case repeat analyses are required; samples of less than 16-oz. are unsuitable for normal testing purposes. In other circumstances it may be necessary to take three or four samples in larger volume, for example in $\frac{1}{2}$ -gallon or 1-gallon cans, especially if important legal or financial considerations or referee testing are involved. Decision rests on the experience and judgment of the sampler who should be aware of what tests are likely to be required. The duplicate sample is usually kept for two months or such longer period as may be deemed desirable.

It is of course imperative that scrupulous care be taken to ensure that sampling equipment and containers are dry and clean, for even slight contamination may vitiate some analytical tests. Sample cans should be provided with screw stoppers, and bottles with well fitting corks or ground glass stoppers. No rubber should be allowed to remain in contact with oil samples. The sample containers should be filled to not more than 90 per cent. of their capacity and stoppers should be tied or wired in place. No wax or sealing-wax should be used. The label should be written in permanent ink or indelible pencil and carry full details of the nature and source of the sample. Labels should be tied or wired on (gummed labels are readily lost), and samples should be kept in a dark, cool, dry and safe store. It is customary to keep a record book for samples, with a cross-reference to relevant documents such as invoices, shipping papers and laboratory reports.

SAMPLING OF GASES

The object of this section is to discuss the problems of gas sampling and the principles and practices to be observed if a sound technique is to be adopted by those who have had no previous experience, and stimulate those who have had even long acquaintance with gas sampling to review their methods critically.

The scope of this section is limited to a consideration of the sampling of fuel gases and gaseous products of combustion; the same principles apply to the sampling of mine airs and other atmospheres. Certain special problems have been omitted, such as those that arise in sampling gas from high-pressure apparatus in which some of the constituents may be liquefied by the pressure.

Brief descriptions of gas-sampling apparatus are given to indicate the nature of the apparatus and enable the reader to decide whether to refer to the original publications.

DEFINITIONS

In addition to those prescribed in various standards, the following expressions are used more particularly in the terminology of the sampling of gases.

A *snap sample* is a sample taken quickly at some time in a much longer period during which the gas being sampled is flowing. At the best a snap sample represents only the gas flowing during the few moments when it is collected, but it may serve as a useful guide in the control of a process. The terms "grab sample", "spot sample" and "control sample" are found in technical literature.

A *continuous sample* is a sample collected gradually and continuously throughout the period during which the gas to be sampled is flowing. The term "accumulative sample" is used by some authors.

An *average sample* is an ideal sample that faithfully represents the whole of the gas from which it was withdrawn. The average sample must be identical in composition with the gas as a whole, whatever the variations in composition and in rate of flow from time to time and from point to point in the gas to be sampled.

A *sampling probe* is a special tube inserted into part of a plant, such as a flue, for withdrawing a sample or some gas to be sampled.

A *sampling pipe* is the pipe and accessory apparatus through which the gas withdrawn for sampling passes from the plant to the sample tube and to any apparatus beyond it such as a pump or a bleeder. The term "sampling line" is used by many authors.

A *sample tube* is a vessel in which a sample for analysis is collected, transported and stored. A sample tube is sometimes called a pipette in American papers.

A *sample holder* is a gas holder used for the collection of a sample when the volume of the sample is greater than can be handled conveniently in ordinary laboratory apparatus.

The *sampling ratio* is the ratio of the volume of a sample to the volume of the gas it represents; or, alternatively, the rate at which the sample is withdrawn relatively to the rate at which the gas represented by the sample is flowing.

The sampling of gases must fulfil fundamental requirements similar to those governing the sampling of solids and liquids, though there are differences in the technique. An average sample is, in effect, the sum of a very large number of instantaneous samples of appropriate individual volume; and, as in the sampling of coal, the number of increments and the size of each increment should be made to depend on the inherent variability of the material sampled. But, whereas coal cannot be completely homogenized without fine grinding, gas in bulk, though not necessarily homogeneous, can rapidly be made so by mixing; on the other hand, if gas is left undisturbed in a holder it becomes homogeneous in time as a result of diffusion and convection.

VOLUME OF THE GAS SAMPLE

The gas flow may be intermittent or the rate of flow and the properties of the gas may vary much or little, cyclically or irregularly. For practical reasons the sample must be collected at some rate above a certain minimum if these variations are to be given their proper weight; this sets a minimum volume for the sample, which must in any case be large enough to provide for its manipulation and analysis, and perhaps also for the preservation of an adequate proportion for subsequent reference.

Sampling in two stages. When, however, the volume of the sample is only a very small fraction of the total volume, as, for instance, when an attempt is being made to collect a 250 ml. sample to represent the gas flowing in eight hours in even a small plant, it is doubtful whether the sampling ratio can be kept constant enough in a single stage of sampling to give an accurately representative sample.

The smaller the amount of the sample the more important is the volume of the connexion to the sample tube. This connexion should be of small diameter and not unreasonably long, though it might sometimes be inconvenient to install the sampling apparatus very close to the plant.

For these reasons the usual practice is first to withdraw a primary sample bearing a moderate sampling ratio to the main flow and then to collect from it the sample for analysis. The overall sampling ratio is the product of the sampling ratios of the two stages.

That part of the primary sample not taken as the sample for analysis may be discarded or returned to the system. The procedure most likely to give a good sample is to take the large primary sample into a gas-holder, mix the gas thoroughly, and then to perform the test or analysis on a small final sample taken from the homogenized primary sample.

CONDITIONS AFFECTING SAMPLING

Stratification. When the composition of a stream of gas varies from point to point in the duct owing to the imperfect mixing of component streams of gas, the effect is known as stratification.

The term stratification might appear to suggest a process of separating a well mixed gas into layers differing in composition, but, in practice, the gaseous constituents do not separate either gravitationally or as a result of centrifugal forces at changes in direction. Everywhere in its passage through a duct the gas tends to become more homogeneous.

Unless the flow is very turbulent, air leaking into the duct, if not in great amount, may tend to creep along the walls, mixing only slowly with the main stream.

An automatic gas analysis apparatus that responds rapidly, such as one depending on the selective absorption of infra-red radiation, or a carbon dioxide recorder working on the thermal conductivity principle, offers a convenient means of rapidly exploring the cross-section of a duct to detect and determine the extent of stratification.

Leakage of air into gas samples. The leakage of air into gas samples is a serious source of error; it can be large, and is most commonly met with in sampling flue gases.

Air may leak into flue gas in several ways. The pressure in a flue is often below the atmospheric pressure, and air may leak in continuously through sight holes and badly fitting doors, and through cracks in the brickwork of the setting. No plant remains free of such defects. The amount of dilution that the waste gases suffer in passing from the combustion chamber to the base of the stack may greatly alter the carbon dioxide content of the sample; flue gases should therefore be sampled as near to the combustion chamber as possible in order to obtain a true indication of the efficiency of combustion. Indeed, leaks can be located and the amount of air leaking into the setting can be determined by analysing samples of flue gas taken from different points in the flue system.

The joint where the sampling probe enters the setting must be tight to prevent air from leaking in at this position. Again, as the pressure in the flue may be below the atmospheric, it is necessary to aspirate the sample; the sampling pipe also must therefore be free from leaks.

Leakage of air into samples being taken from systems under pressures above atmospheric can only occur through negligence. Contamination of the sample with air, once the sample has been taken, is discussed in a later section.

Suspended matter. Where the gas to be sampled carries in suspension matter such as fly-ash or soot, or tar-fog or other droplets, and where the deposition of any of these might block the sampling system, steps must be taken to free the gas from suspended matter at an early stage in sampling. Further, the determination of certain of these non-gaseous components may be required, and methods for sampling them are appropriately considered as part of the technique of gas sampling.

Owing to their inertia particles carried in suspension undergo a process of sorting and concentration. All the particles, but especially the larger and heavier particles less able to follow changes in the velocity and direction of

the gas, tend to find their way to places where the gas velocity is least, leaving the smallest and lightest particles where the velocity of the stream is greatest. The larger and heavier particles tend to sink more rapidly under gravity to the floor of a horizontal duct, or may fail to be raised by gas ascending a vertical duct.

Sampling of gas containing dust. When dust suspensions are being sampled quantitatively it is essential that the velocity of the gas entering the sampling probe be the same as the velocity in the zone from which the sample is being taken, and that the probe should face upstream. If the velocity of the sample entering the probe is too high, the proportion of suspended matter collected is likely to be too low. Therefore, when it is desired to take a gas sample without including the suspended matter, it might be advantageous to use a probe with as small an aperture as practicable, to position the probe so that it faces downstream, and to withdraw the sample at the highest possible velocity. If there is much suspended matter it may be necessary to use a filter.

The inertia of the particles may be utilized to provide an effective method for the removal of suspended matter from a gas stream by making the gas pass through an apparatus in which sudden changes in velocity and direction are imposed on it. An apparatus using this principle for the quantitative precipitation of dust is the jet impinger developed by the United States Bureau of Mines in 1922. The "Midget Impinger" was described in 1939⁶. The gas carrying particles in suspension is aspirated through a nozzle one millimetre in diameter at a rate of 0.1 cu. ft. per min., the pressure loss being about 12 in. water gauge.

Tar fog separator. The removal of mists such as tar fog is relatively difficult, because the smaller the particle or droplet the more sudden must the changes in velocity and direction be to precipitate it. A satisfactory apparatus, designed for separating tar fog, but equally suitable after slight modification

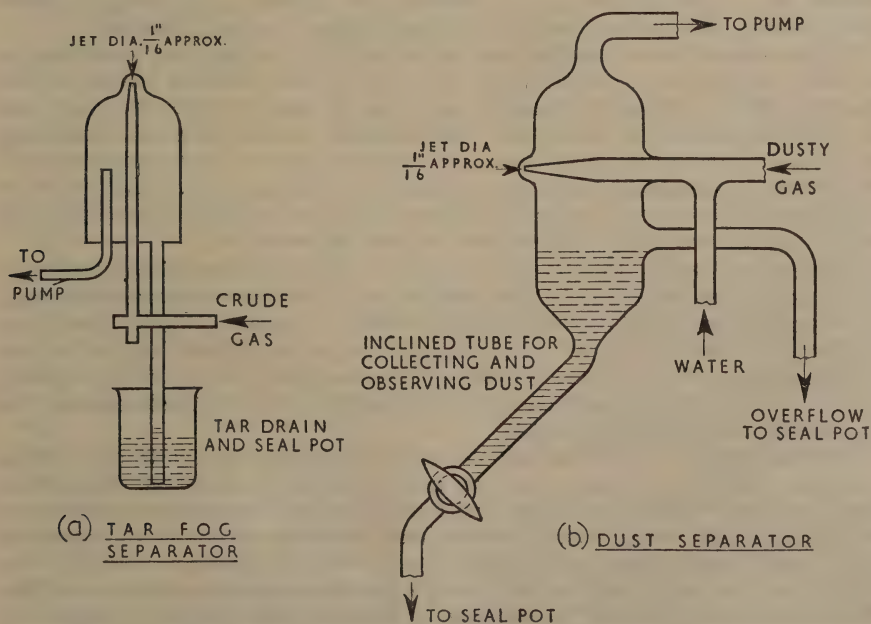


FIG. 2. Tar fog separator.

for the removal of solid suspended matter⁷, and is shown diagrammatically in Fig. 2. A jet of the gas is directed at a high velocity into a cup-shaped depression in an obstructing surface and constrained to change its direction through nearly 180°. The droplets thrown out adhere to the surface, coalesce and drain away.

A little water supplied to the nozzle will remove dust deposited and some kind of pump must be used because effective filtering inevitably introduces a high resistance to the flow of gas.

Filters for removing dust. Dust may be removed in a chamber loosely packed with fibrous material such as slag wool or glass wool, or by means of a porous partition of ceramic material, carborundum or sintered glass. The dust filter should be placed where the temperature never falls below the dew point of the gas, for the condensation of moisture in a filter causes serious resistance to the flow of the gas.

Quantitative sampling of dust. In a position suitable for the sampling of dust, such as after a long straight length of the duct, the velocity distribution would be symmetrical about the axis of the duct. If, then, two pitot tubes are arranged, one in the mouth of the sampling probe placed facing upstream and the other at the same distance from the axis of the duct as the probe, but on the other side of the axis, and also facing upstream, the speed of sampling can readily be adjusted so that the indications of the two pitot tube manometers are equal. The velocity of the gas entering the sampling probe may then be taken as equal to that of the gas approaching the probe.

This principle is utilized in a gas sampling apparatus patented in the United States.⁸

The quantitative filtration of dust. A simple method⁹ for sampling industrial dusts which enables the dust to be recovered for weighing and examination, consists in drawing the dust suspension through a pad of naphthalene supported on a stainless steel gauze, passing the filtered gas through a meter, and isolating the dust subsequently by subliming the naphthalene.

If the composition of the dust and the nature of the subsequent examination are such as to make it necessary to recover the dust without having heated it above 50° C., crystalline salicylic acid can be used for the filter pad, and the dust recovered by extracting with alcohol, centrifuging and extracting with ether. Dusts of low concentration, in the range one to two mg. per c.m., are efficiently caught on pads three to four millimetres thick. Gas flows of up to 12 litres a minute per square centimetre of filter area can be induced through such a pad by means of an air-ejector type of aspirator.

Condensate. By the time that the flue gas from a fuel containing hydrogen has cooled to the atmospheric temperature, water vapour will have condensed. It is shown later, in the section dealing with the solvent action of confining liquids, that the solution of even so soluble a gas as sulphur dioxide in such condensate has an insignificant effect on the analysis of a flue gas as usually carried out; but the acid solution formed is strong enough to attack seriously the corrodible parts of the apparatus.

The condensate may be enough to form with dust present in the gas a mud that may block the passages, and yet not be enough to flush the pipe. It has been proposed¹⁰ when sampling dust-laden gas, such as the flue gas from a cement kiln, that water should be admitted at the entry end of the sampling probe and drawn through the sampling pipe with the aspirated sample. The water would be recirculated so as to reduce the solvent action as far as possible. When dust-laden gas must be sampled it is essential to avoid blockages even though the means adopted may introduce a slight error.

Mixing. When the gas to be sampled is made up of two or more component streams and when there is little natural turbulence it may be necessary to introduce some special mixing device into the main to ensure that any sample represents all the component streams in their true proportions.

A rotating paddle may be the most suitable means in some instances, but a stationary device would be preferable. For example, it might be possible to introduce into the main a system of baffles to create a suitable turbulence some distance before the sampling point. The baffles might be arranged so as to force the gas successively through two narrow slots, the second at right angles to the first, or, a central disc followed by a plate with a central hole should serve to mix the gases.

To ensure good mixing, the flow must be highly turbulent at the restricted points; but turbulence at other places does not necessarily contribute to the effectiveness of the mixing, and, by wasting energy, may cause an undesirable permanent pressure drop. If it is essential to recover as much as possible of the pressure drop caused by accelerating the gas at the restrictions (as it might be with a flue working under natural draught) the cross-section of the duct should be changed gradually on both sides of the obstruction: the baffles might, for example, tend towards a gentle conical form.

It might be advantageous to introduce into the duct carrying the main gas stream an arrangement of partitions, as shown in Fig. 3, to sub-divide the gas stream into separate neighbouring portions and bring them together in a different grouping.

The diagrams (a) to (e) in Fig. 3 represent successive cross-sections through

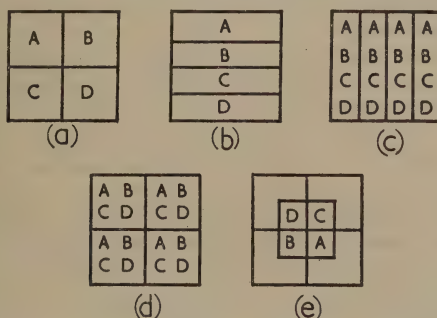


FIG. 3. Successive sections through gas sampling mixer.

the mixer. The partitions (a) having divided the cross-section into quarters, are inclined (in a manner that is more easily visualized than either drawn or described) so as to direct the gas from each quarter into a layer as in (b). This can be done without seriously obstructing the path of the gas. Diagrams (c) and (d) represent a second unit exactly like that of diagrams (a) and (b) but in the reverse order and rotated through a right angle. Each layer in (b) is divided into four by the partitions in (c) and each layer in (c) then has some of the gas from each quarter in (a). Partitions then direct the gases from the layers in (c) into the quarters in (d). Each quarter in (d) now has some of the gas from all the quarters in (a).

The process may be taken further by increasing the number of sub-divisions (which, incidentally, increases the complexity of the arrangement and the tortuosity of the gas passages) or, alternatively, another simple four-fold unit can be applied to one of the quarters, or, as shown in (e), to the central part of (d), and the next stage of mixing could then be applied to a part of the main gas flow, thus reducing the sampling ratio.

The principle of using partitions to divert parts of a stream has been used successfully to correct the distribution of airborne pulverized coal¹¹ and in the riffle sample divider shown in Fig. 1 above.

Sampling from the cross-section of a duct. If thorough mixing cannot be assured, it may be necessary to divide the cross-section of the duct into a number of imaginary areas and to take samples simultaneously from the centres of these areas, each at the correct rate, as determined by pitot tube measurements, for example, by Collett's apparatus⁸. Such a procedure, if carried out punctiliously, would demand much labour or elaboration, and attempts have been made, from time to time, to devise a simple way of carrying out this principle by means of a bundle of tubes of different lengths, or by means of a perforated tube inserted across the gas stream. But it is doubtful whether such arrangements can be relied on to fulfil accurately the desired condition of taking from each zone a quantity of gas related to the flow. A sampling probe, the immersion of which is varied by a motor-driven cam so as to explore the cross-section of the duct automatically, has been described by Lloyd¹². The speed of traversing could be made inversely proportional to the rate of flow of the gas, the probe being moved most slowly across that part of the gas stream where the velocity is greatest.

Of the several different methods, the perforated tube placed across the diameter of the duct is probably the simplest method of approaching the desired conditions. As the velocity at which the gas flows is nearly zero along the wall of the duct, and reaches a maximum along the axis of the duct, it is clear that the gas must be drawn off at a greater rate nearer to the centre compared with that at which it is withdrawn nearer to the wall; it has therefore been suggested that the sizes of the holes in that part of the sampling tube within the main should be graded according to their position in the cross-section of the main, the largest hole being nearest to the centre. An alternative and simpler method is for the holes to be of uniform diameter and for their spacing to be graded so that they are closer together nearer the centre.

The reduced pressure in the sampling probe, causing the gas to pass into the probe, will not be distributed in the probe with its greatest value where it should be to give the desired flow; it is difficult to compute the diameters or spacing of the holes, and scarcely practicable to make the probe so that it will work accurately especially at low rates of withdrawal of the sample.

The smaller the holes the better the conditions for sampling, but the more likely the holes are to become choked. As blockages may be caused by deposits from the gas stream, provision must be made for frequent inspection and cleaning.

The American Society for Testing Materials has proposed a method of sampling steam¹³ which uses a tubular probe closed at the end and perforated along its side. Steam pipes are divided into three ranges according to their internal diameters, namely, from 2 to 6 inches, between 6 and 12 inches and over 12 inches, and the recommended number of holes, equally spaced along the probe, is 4, 6 or 8, respectively, for these three ranges of pipe size. The total cross-section of the perforations must be no more than two-thirds of the cross-sectional area of the probe and, as the velocity of the gas entering the probe must be equal to that of the gas as it approaches the probe, the size and proportions of the probe for a given situation and sampling ratio can be determined, and the probe made accordingly.

Sampling from a single point. Usually in practice gas enters a duct simultaneously at all parts of the cross-section of the duct. The velocity of the gas is greatest near the axis of the duct and least near the walls; but as far as gas sampling is concerned, if the gas is uniform when it enters the duct, the effect

of differences in speed at various points in the cross-section of the duct is only to introduce differences in the time the gas takes to reach the sampling point; and unless the composition of the gas entering the duct is changing rapidly the differences in composition at various points in the cross-section of the duct due to differences in velocity will be insignificant; and if the composition is changing rapidly, sampling will be unsatisfactory whatever method is used.

When the flow is turbulent (as it usually is) the average velocity of the stream is about 80 per cent. of the maximum velocity, and the region at which the local velocity is equal to the average is roughly three-quarters of the way from the axis to the wall. Thus, the gas in the zone three-quarters of the way from the axis to the wall would lag only a few seconds behind that near the axis.

Thus it is only in exceptional circumstances, when the gas carries matter to be sampled in suspension or is highly stratified on entering the duct, and when turbulence is feeble or absent, that it is necessary to use one of the sampling probes intended to compensate as far as possible for variations in both the composition and speed of the gas in the cross-section of a duct. It may be necessary sometimes to withdraw the sample simultaneously from a number of points in the cross-section of the duct to compensate for local variations in the composition due to persistent stratification, but in practice it should seldom be necessary to make an individual adjustment of the sampling rate from each point in the cross-section. In everyday practice it should be sufficient to withdraw the gas sample from a single point at or near the axis of the duct. It is not satisfactory to take a sample from a large duct unless the tee connexion projects well into the duct, except when the sampling ratio is unusually great.

Sampling the components of a mixture. If thorough mixing cannot be assured, or if the sample cannot be made to represent each element of the cross-section, the only remaining possibility is to sample the components separately and calculate the analysis of the final mixture from the analyses and proportions of the components.

Dead Spaces. Clearly it would be unsatisfactory to insert the sampling probe in a part of the system where the gas is stagnant. It is necessary to choose as the sampling point a place where the main gas stream will flow past the entry to the sampling probe. Gas must be made to pass through the sampling pipe fast enough to ensure that the composition of the gas in the sampling pipe follows with the least possible lag any change in composition in the main stream. The sample tube or sample-holder must be connected to the sampling pipe by means of a tee, connected so that the sample for analysis is taken from the gross or primary sample drawn from the main; a suitable tee-connexion is discussed below.

Eddies. Immediately following abrupt obstructions and sudden changes of cross-section, pockets may occur in which the gas, although it may be in violent motion, is circulating in eddies without full interchange with the main stream. In order to avoid these pockets, it is recommended that sampling probes should not be inserted in a main near such disturbing features.

When combustible gases and oxygen are present together in a hot flue, and turbulence is insufficient to bring them into contact so that combustion can be completed, flue gases should be sampled as near to the exit from the combustion chamber as possible, in spite of the inconvenience of sampling hot gas, because further combustion may occur in the flue and yet be lost to the plant.

In choosing a sampling position all the possibilities should be thoroughly explored in accordance with the principles that have been mentioned. With

a new plant, or when new or special work is being started at an existing plant, sampling is often done at a number of points at first, and subsequently, in the light of experience, discontinued at some of them. Although it is laborious, a number of samples should be taken at various distances across a main or duct at the position chosen for sampling, and the analyses of these samples compared with those of composite samples taken, for example, by means of the perforated tube already described.

INTERACTION BETWEEN THE SAMPLE AND THE MATERIALS OF THE APPARATUS

Most fuel gases and flue gases contain constituents that react to some extent with materials used in the construction of sampling apparatus, but for ordinary practical purposes the rate and extent of the action do not usually invalidate the sample in the short time during which the sample is in contact with the sampling system. But in any precise investigation, particularly if certain minor constituents of the gas are of special interest, careful consideration should be given to whether such effects may or may not become appreciable. Interaction between the sample and the materials of the apparatus may take the form of chemical attack and corrosion, or solution, or permeation.

Rubber Tubing. Rubber connexions are very much used in gas sampling. They should be kept as short as possible.

The permeability of rubber to carbon dioxide is easily demonstrated, but a length of rubber tubing that is no longer than will fulfil requirements would not cause the carbon dioxide content of a flue gas sample flowing through it to be reduced by an amount sufficient to be detected by the methods of analysis used in controlling the operation of a furnace.

Most sulphur compounds in vapour or gaseous form react with rubber to some extent. Rubber absorbs hydrocarbon gases and liquids such as tar fog. For example, it has been observed that abnormally high values can be obtained for the calorific value of a lean gas, determined in a Boys calorimeter, when the gas has to pass through a rubber connecting tube through which a rich gas has flowed in a previous determination. When the rich gas passes through the tube, hydrocarbons from it dissolve in the rubber; afterwards when their partial pressure is reduced because a lean gas is passing, they come out of solution in the rubber and give a fictitiously high calorific value for the lean gas. The value gradually falls to normal as the lean gas eventually carries the hydrocarbons away. There would be a corresponding reduction in the calorific value observed for the rich gas if the determination were made before equilibrium became established.

Modern synthetic substitutes for rubber are probably more inert and less permeable than natural rubber; the main disadvantage of tubing made of these synthetic materials seems to be their inferior ability to stretch.

Joints. A joint that almost completely prevents the exposure to the gas of rubber connexions between lengths of glass tubing is shown in Fig. 4. A glass sleeve is fitted over the ends of the glass tubes to be joined, short lengths of rubber tubing being used to seal the ends of the sleeve.

It is particularly important to prevent hot gases from coming into contact with rubber connections. When a high temperature precludes the use of rubber, the sleeve shown in Fig. 4 can be sealed by means of a quick-setting cement such as zinc oxychloride, or one of the dental cements. Zinc oxychloride is readily made by making zinc oxide into a paste with saturated zinc chloride solution. It sets rapidly and therefore should be made up only in small quantities as required. The joint can easily be broken by dissolving the zinc oxychloride cement in concentrated hydrochloric acid.

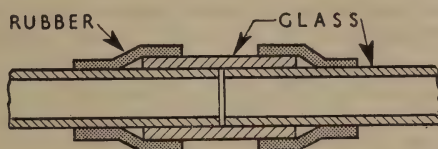


FIG. 4. Rubber sleeve jointing for glass tubes.

Corrosion of sampling apparatus. Glass, fused silica and glazed porcelain are not acted on by any of the constituents of fuel gases or flue gases. Silica at high temperatures is permeable to hydrogen and some other gases, but this fact causes no trouble when hot gases are sampled through a water-cooled tube.

The metals likely to be used in the construction of gas-sampling apparatus are iron (which will inevitably acquire a coating of scale) copper and brass, lead and composition tubing. All these metals are attacked by hydrogen sulphide, by oxides of sulphur and by oxides of nitrogen. Under certain conditions iron and its oxide scale react with oxides of carbon, and with hydrogen, oxygen and water vapour.

If fuel gases in the widest sense are considered, it should be added that copper and brass react with ammonia, acetylene, hydrocyanic acid and cyanogen. Aluminium or tin tubing can be used where any hydrogen sulphide present must not be removed before analysis.

CONFINING LIQUIDS

Ideally a confining liquid should have no solvent action on the gas with which it is in contact. This ideal is most nearly attained with mercury; but even mercury is attacked by some gases, for example, hydrogen sulphide. Mercury is costly, and inevitable losses of mercury cause appreciable operating expense.

Thermal expansion of mercury. A sample tube that has been filled ready for use with mercury should always be left with one cock open; this is especially necessary if the tube is to be carried in the hand. A slight rise in temperature causes the mercury to expand with a virtually irresistible force that will at least force the plug of one cock out of its barrel; even if the plug does not fall and break, the mercury will contaminate the barrel and necessitate the cleaning and re-greasing of the cock; or the looseness of the cock may escape notice when the tube comes to be used. If the cocks are very stiff, the tube may burst.

The solvent action of confining liquids. Sometimes, for example in sampling flue gases, water used as the confining liquid may be kept out of contact with the gas by means of a film of a mobile and non-volatile oil on the surface of the water.

With many gases and gas mixtures water or certain aqueous solutions can be used as confining liquids because their solvent action on the constituents of the gas is small enough not to affect the composition of the sample seriously.

The solvent action of water. Fig. 5 shows how the carbon dioxide content of flue gas may be altered if the gas comes into contact, and attains equilibrium at atmospheric pressure and temperature, with various proportions of water. It will be seen that the high solubility of carbon dioxide may lead to a serious error in the proportion of this constituent measured by analysis; the percentages of the other constituents are liable to alteration consequently. The curves represent four hypothetical flue gases containing respectively 5, 10, 15 and 20 per cent. of carbon dioxide and 15, 10, 5 and 0 per cent. of oxygen, the nitrogen content in each instance being 80 per cent.

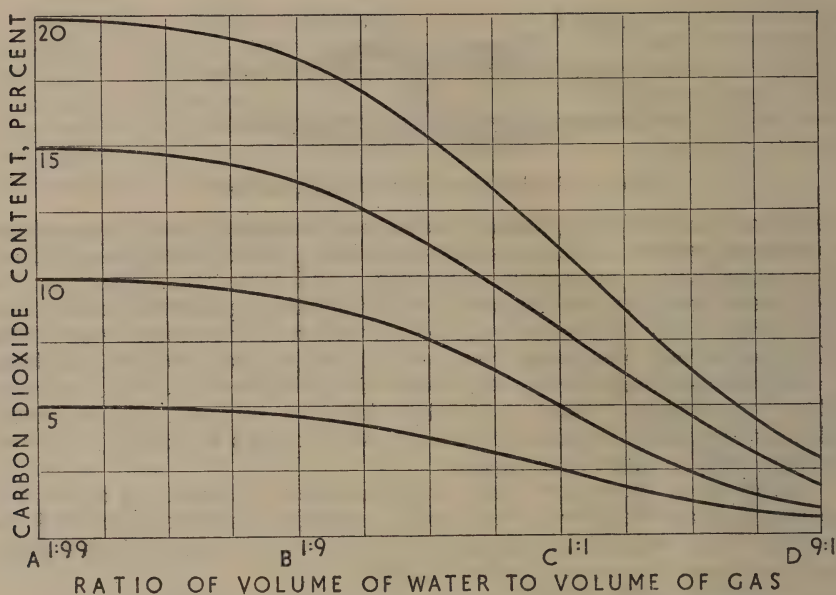


FIG. 5. Effect of solvent action of condensed water on CO_2 content of gas sample.

It was reasonably assumed for this computation that the solubility of each constituent is not modified by the other gases dissolving at the same time. It was also assumed that the water used as the confining liquid would be saturated with air, and allowance was made for the oxygen and nitrogen already in solution.

The conclusions are that

- (1) if the volume of the water is one-thousandth that of the gas, which is about the amount of water that would wet the walls of a sample tube, the effect on the composition of the gas would be quite negligible;
- (2) if, in order to leave the sample under a slight pressure, 2.5 ml. of water were forced into a 250 ml. sample tube, the conditions would be those of point A, and at equilibrium the carbon dioxide content of any flue gas would be about 95 per cent. of the true figure, and the error might be significant;
- (3) if the sample tube were one-tenth full of water the carbon dioxide content of the flue gas would be reduced to about 91 to 92 per cent. of its true value;
- (4) when the sample tube is half full of water (as it might be if that part of the sample not required in an analysis were retained for subsequent reference) the carbon dioxide content observed at equilibrium is only about 50 per cent. of the true value;
- (5) if the sample is in equilibrium with nine times its volume of water the carbon dioxide content becomes less than 10 per cent. of the original content; such changes could happen in a bad arrangement in which the gas in being aspirated comes into contact with a large volume of water.

The solvent action of condensates. Vapours present in the gas may condense if the gas is cooled. It is often pointed out that the liquids formed by this condensation may dissolve some gaseous constituents of the gas; and it is often stated that the analysis of the gas may be noticeably affected by the

solvent action of the condensate. However, it can be shown that the volume of the water condensed from a flue gas, whatever the hydrogen content of the original fuel, is insufficient to dissolve enough carbon dioxide to affect the analysis significantly. For example, the dew point of the products from burning coal gas might be as high as 60° C. Each millilitre of dry gas would be scrubbed by about 0.00012 ml. of condensate, and the effect on the analysis can be seen from Fig. 5 to be negligible.

Sulphur dioxide is about 44 times as soluble in water as carbon dioxide, but even the sulphur dioxide content of a flue gas could not be reduced by solution in the condensate to an extent that could be detected by the ordinary flue gas analysis in which sulphur dioxide and carbon dioxide are lumped together as carbon dioxide. If, however, the sulphur dioxide content is being determined separately the loss by solution in the condensate, though remaining small, might become significant and have to be taken into account.

The solvent action of aqueous solutions. The solubilities of gases in aqueous solutions of suitable chemicals are lower than in water alone, and some of these solutions make satisfactory confining liquids, although not all of them are convenient. Gray¹⁴ has shown that a solution of magnesium chloride can be used as a confining liquid for gases containing high percentages of carbon dioxide, provided that the gases do not remain in contact with the solution for long periods. If, however, the gas is in contact with the solution for as long as twenty-four hours then even the strongest solution is unsatisfactory. Gray's results also show the serious effect of agitating the gas sample with the confining liquid.

Kobe^{15,16} and his co-workers have determined the solubility of carbon dioxide in several solutions of inorganic compounds. Of the solutions investigated by them, calcium chloride dissolves carbon dioxide the least. It has, however, the disadvantage that the solution is very viscous and corrosive; it does not dry when spilt but remains sticky. Magnesium chloride is less viscous and has only a slightly greater solvent action on carbon dioxide. It suffers, however, from the defect that if alkaline reagents come into contact with it magnesium hydroxide is formed and readily blocks the connecting tubes; in the absence of alkalis, however, it is quite satisfactory. A solution containing 20 per cent. by weight of sodium sulphate and 5 per cent. by volume of sulphuric acid is recommended as the best confining liquid for general use in industrial practice. The solution crystallizes below 59° F., but generally, though perhaps not always, it is possible to avoid working below, say, 60° F.

ASPIRATORS

In many installations the pressure of the gas to be sampled is too low to cause the gas to flow through the sampling system, and some kind of pump is necessary to cause the required flow.

The bulb aspirator. Rubber aspirating bulbs, squeezed by the hand, are widely used for aspirating snap samples from flues. The use of these bulbs over long periods is tedious and fatiguing.

Liquid displacement aspirators. There are many forms of aspirator where the gas is made to flow into a vessel by allowing a confining liquid to flow out. Apparatus of this type is frequently used not only to cause the gas flow but also to contain the sample.

In a neat and portable aspirator due to Stephenson¹⁷ the rate of flow of the water is kept practically constant by the Mariotte bottle device, the head of water being constant and equal to "h" in Fig. 6, modified by the back pressure of the liquid seals, all of which should contain the same depth of water. A continuous flow can be maintained by inverting the aspirator

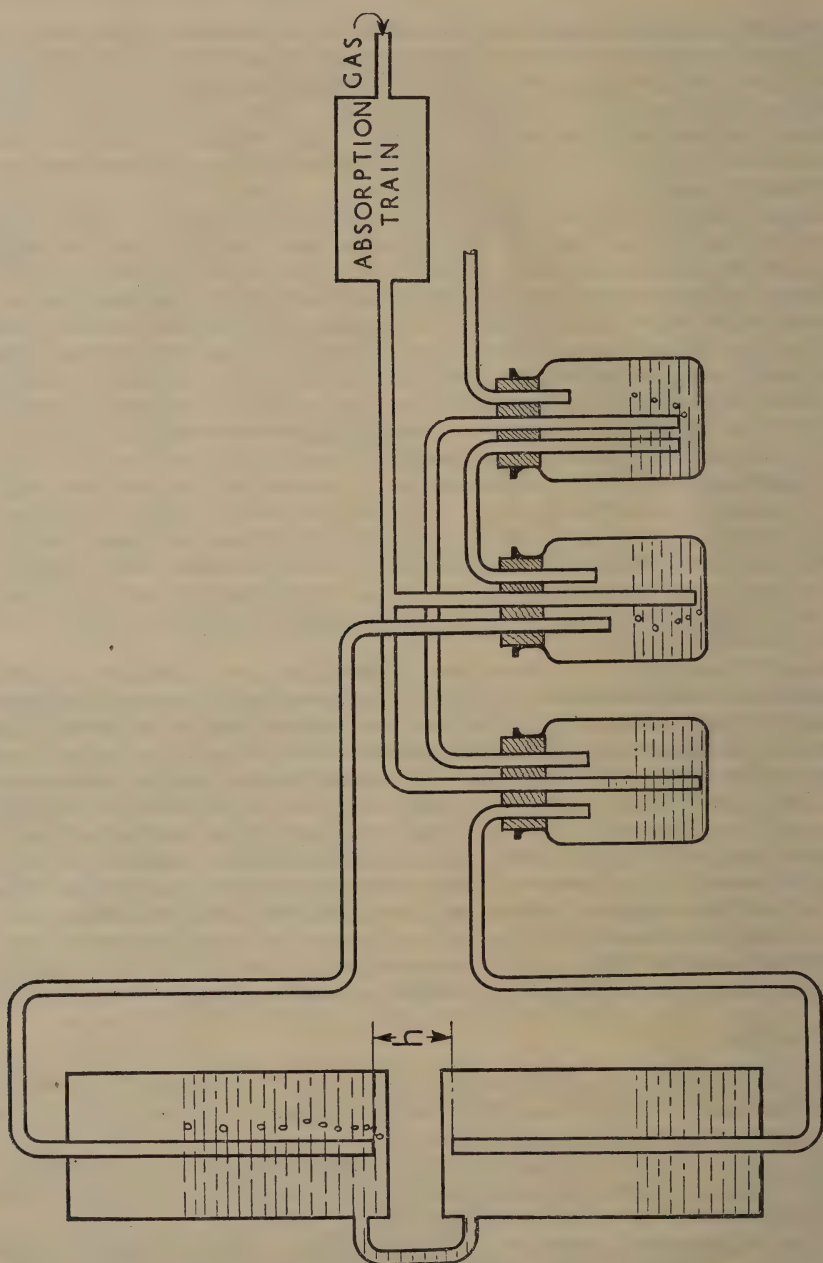


FIG. 6. Stephenson aspirator.

repeatedly. This apparatus was designed for aspirating a flow of gas through an absorption train, and the liquid seals are arranged so that, whichever vessel is uppermost, the gas always flows in the same direction through the absorption train.

Mechanical aspirators. For supplying a continuous flow of gas for long periods an automatic, power-operated arrangement is required. Two main

types are available: motor-driven pumps, and ejectors operated by compressed air or water.

Motor-driven aspirators. Use is frequently made of rotary blowers, both of the gear-pump or Roots blower type, and of the kind in which the gas is driven by a vane projecting from an eccentric drum revolving within another drum. Some examples of these small blowers are unsatisfactory: they quickly become overheated; adequate lubrication is difficult to achieve without contaminating the gas with oil, or clogging the gas passages with grease. It is sometimes difficult to obtain a steady slow gas flow; probably the best way is not to throttle the flow but to allow the pump to deliver more gas than is required, and to by-pass or bleed off the unwanted gas.

Of the reciprocating pumps those having a diaphragm or bellows, instead of a piston, are positive in action, do not leak, and do not contaminate the gas.

However, all these pumps introduce a pulsation in the sampling pipe that causes a tidal interchange of gas between the sample tube and the sampling pipe. The individual pulsations may appear trifling, but they may be repeated many times a minute. It can be demonstrated³⁴ that the sample collected may be so heavily weighted in favour of the gas most recently passing the sampling tee-connection, that the gas collected approximates to a snap sample.

The pressure pulsations can be smoothed out, and this most serious effect minimized, by installing at the inlet to the pump a reservoir such as a five-gallon (or larger) drum and a restriction such as a small orifice.

Ejector aspirators. The laboratory type of filter pump, in which the flow of air or gas is induced by a jet of water, offers a convenient means of drawing a stream of gas through a sampling pipe.

Filter pumps will evacuate a system down almost to the vapour pressure of the water, and will consequently overcome a high back pressure; but they need a head of water of at least 20 feet; and, as they may pass about 100 gallons of water per hour, they must be considered wasteful. When a water pump is used continuously on tap water, trouble may arise because of the blocking of the nozzle by scale or by suspended matter carried in the water or the gas, or sometimes by calcium carbonate formed as a result of the reaction between hard water and carbon dioxide in the gas.

If the water and the entrained gas are discharged from the filter pump into a suitable vessel, from which the water is allowed to flow through a raised offtake, the filter pump can be used to deliver gas against a pressure; but in passing through the apparatus the gas is vigorously scrubbed by the water, and this may preclude the use of such an arrangement. On the other hand, the scrubbing action of the water has been exploited¹⁰ to free flue gas from dust before delivering the gas through the sampling pipe to an automatic gas analysis apparatus, solution of the soluble gaseous constituents being minimized by re-circulating the water by means of a motor-driven pump.

An arrangement known as a "tail pipe" is often used to withdraw flue gas through a sampling pipe. Water in passing the side arm of a tee-piece entrains the gas and induces a flow of gas in the form of bubbles separated by drops of water.

Compressed air, instead of water, may be used in an ejector to induce a flow of gas. One carbon dioxide recorder, when an aspirator is necessary, makes use of an air ejector, actuated by the chimney draught, to induce the required flow of flue gas through the instrument.

CONTAINERS FOR GAS SAMPLES

Several different sampling containers that might have their uses in special circumstances have been described in the literature. The Gooderham holder¹⁸ has a bellows-like structure and is built up from corrugated discs (Taylor

rings). Gas can be stored in it out of contact with confining liquids; the one described by Gooderham has a capacity of $7\frac{1}{2}$ litres and a dead space of only 100 ml., but it can be evacuated completely if necessary.

An alternative to the glass sample tube and confining liquid is a suitably designed metal plunger-pump, such as that described by Lee¹⁹. The piston is made gas-tight by a leather ring held in a groove formed between the peripheries of two plates, and the leather ring can be forced radially outwards into gas-tight contact with the wall of the cylinder.

For practical reasons the special solutions already mentioned can be used as confining liquids on the small scale only; they would be unsuitable for filling the tank of a large gas-holder and it would be necessary to use water to seal the bell. It would be desirable to adopt special means to ensure that the gas sample, while it is accumulating or being stored, does not come into contact with a large volume of water. A large part of the surface of the water in the tank, under the bell, can be kept out of contact with the gas by means of a floating raft only a little smaller in diameter than the bell of the gas holder. But the blanketing of the free surface of the liquid does not reduce the total amount of gas that will dissolve, although the rate at which the soluble gases are removed by solution may be greatly reduced; the soluble gases will dissolve in the accessible confining liquid and will diffuse in time throughout the whole of the confining liquid. If, however, the tank could be reduced to a narrow annulus containing only enough water to seal the skirt of the bell, the total amount of gas dissolved would be limited.

THE SAMPLING PIPE

For the sampling pipe in a permanent installation, lead tubing of generous bore (e.g. $\frac{3}{8}$ in. I.D. and $\frac{3}{4}$ in. O.D.) is satisfactory. The lead pipe should lie on a continuous shelf-like support to prevent it from sagging. Hot gases will almost always be cooled below the dew-point, and any such permanent installation should have a fall of, for example, 1 in 20 in the direction of the gas flow. A drain and water seal should be provided at the lowest point and at any point that is lower than the pipe on both sides of it. It is imperative, if the sample is being aspirated through the sample pipe, to provide a water seal, containing only a little water, and arranged so that if a blockage occurs the seal breaks and admits air, thus preventing any trouble or damage that might occur if the aspirator were allowed to evacuate the system.

An iron sampling pipe is often satisfactory, but with moist gases is likely to become choked by rust.

The prevention of blockages. In any permanent sampling pipe provision should be made at suitable points for the insertion of a rod to clear blockages, and arrangements should be made, if possible, to keep the pipe clear by blowing it through regularly with compressed air, for example, once a shift.

THE EFFECTS OF TEMPERATURE ON THE SAMPLE

If a sample must be taken from a point where a reaction is still going on, a sample that has cooled gradually may not have the same composition as it would have had if it had been suddenly chilled: the combustion of unburnt gases may be completed while the sample is being withdrawn from the sampling point. Thus there is a tendency for a flue gas analysis to underestimate both the oxygen and combustible gas contents if the sample has been taken through a hot probe.

Water-cooled sampling probe. It is therefore essential in such instances to use a water-cooled sampling probe, which, incidentally, will protect the gas-sampling apparatus against damage by heat.

One form of water-cooled sampling probe has been described by Nichols²⁰ and is shown at (a) in Fig. 7. The tube had an internal diameter of only $\frac{1}{16}$ in. in order to secure a high gas velocity, which increases the rate of heat transfer and the suddenness of the chilling. Arrangements were made to clear blockages, when necessary, by means of a steel wire. The effectiveness of this probe in preventing further burning from taking place in the sampling system

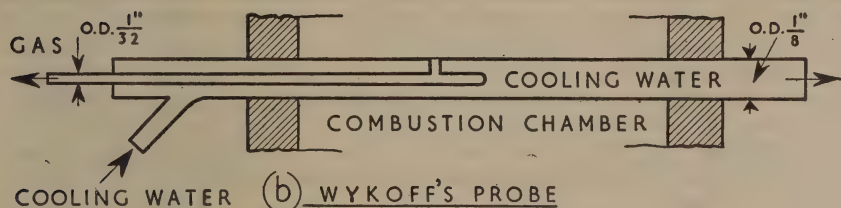
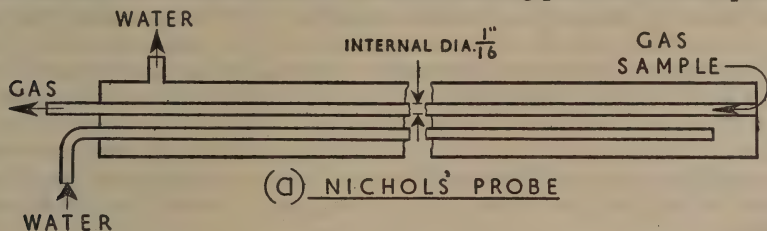


FIG. 7. Gas sampling probes.

may be judged by the fact that samples taken at high velocity from near the surface of the fuel bed in a gas producer contained about equal volumes of carbon dioxide, carbon monoxide and oxygen.

Another probe, shown at (b) in Fig. 7, has been specially designed²¹ to quench the reactions taking place, and to impede as little as possible the flow of the gases being sampled. By arranging for the cooling water to flow in one direction only it was possible to make a probe with an external diameter of only $\frac{1}{8}$ in., the internal diameter of the gas tube being less than $\frac{1}{32}$ in. The smaller the probe the more difficult it is to achieve adequate cooling, and in some special investigations in combustion chambers with high rates of heat release it was necessary to raise the pressure of the cooling water to prevent it from boiling; but in general industrial applications there should be no difficulty in keeping a water-cooled sampling probe cool.

A water-cooled probe should be made of stainless steel to secure mechanical strength and chemical inertness.

THE KIND OF SAMPLE

Whether a snap sample or a continuous sample should be taken is determined by the conditions prevailing and the purpose of the sample.

If the composition of a stream of gas is uniform a sample, of whatever duration, taken at any time, is a representative sample.

If the composition of the gas is varying but the rate at which the gas is flowing is constant, it is necessary, in order to obtain an average sample, to collect a continuous sample at a uniform rate. An alternative method approximating to the taking of a continuous sample would be to take a succession of snap samples at frequent and regular intervals of time, and mix them in

equal proportions. Whether snap samples are taken at long intervals or very frequently depends on the conditions; often the conditions are not known, and one should err on the side of taking more samples than are necessary to achieve the required accuracy.

In general, however, the composition, the rate of flow and the pressure of the gas all vary with time, and special methods may have to be adopted to ensure that the sampling ratio is constant enough. If, at the sampling point, there are local differences in the composition of the gas, owing to the imperfect mixing of component streams differing in composition, it is necessary to mix the gas to ensure that it is homogeneous before it is sampled. Where at any given instant the composition of the gas is the same at all points in the cross-section of the duct, it is merely necessary, in order to take an average sample, to collect the sample at a rate that is a constant fraction of the rate at which the gas is flowing, in other words, to keep the sampling ratio constant.

Snap samples. When the gas analysis apparatus is portable, snap samples are usually taken directly into the measuring burette of the apparatus. If, however, the analysis cannot be done at the plant, or if the gas analysis apparatus is not portable, snap samples may be taken in a plain gas-sampling tube, Fig. 8, by allowing the confining liquid to run out rapidly.

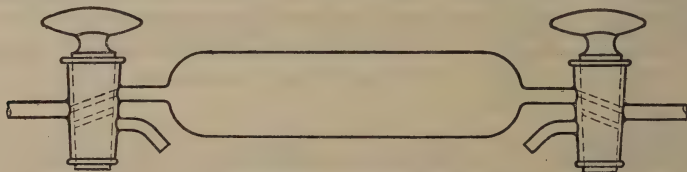


FIG. 8. Gas sampling tube: plain type.

It is sometimes necessary, as, for example, in taking a snap sample of air from an inaccessible place, to use an evacuated sample tube. It is not difficult

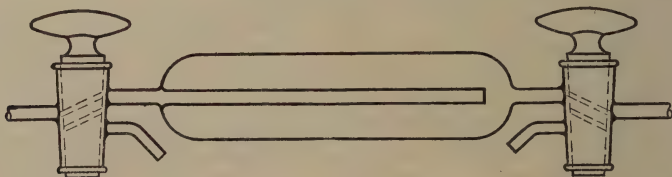


FIG. 9. Huntly sampling tube.

to devise a remote control for opening the cock and closing it again after taking the sample; a Bowden wire suggests itself for this purpose.

The sampling of air in mines²² is often carried out by breaking off the sealed tip of an evacuated glass bulb and re-sealing it with a rubber cap. But the inconvenience of transferring the sample to the gas analysis apparatus, and of re-evacuating and re-sealing the bulb, make this method unsuitable for general adoption.

Sampling by the displacement of air. It is a common practice to take a sample by making the gas pass through a plain sample tube for some time and then to shut off the sample tube. The sample taken in this way is neither a snap sample nor an average sample but approximates, though not closely, to a snap sample at the time when the cocks of the tube are closed.

The gas enters the sample tube as a fine jet that tends to leave pockets of the original air at the shoulders of the tube; the gas also mingles with the residual air. It can be shown by simple experiments that the volume of the

gas passed through a plain sample tube must be at least six times the volume of the tube in order to displace the original gas sufficiently to reduce contamination by the residue of the previous gas to the point where an Orsat apparatus would not detect it. Clearly, a Huntly tube, Fig. 9, would be quite unsuitable for sampling by displacement of air.

Sampling at a constant rate. If the gas sample is aspirated into a plain sample tube, Fig. 8, the confining liquid, usually mercury, being allowed to drip from the lower cock, the rate at which the mercury flows out depends on the head of mercury above the point from which it is issuing. The rate at which the sample passes into the tube therefore diminishes progressively, and at the end of the sampling period may be only a fraction, perhaps a half, of what it was at the beginning.

The Huntly tube²³, Fig. 9, was intended to overcome this objection automatically, but as Weight²⁴ has pointed out, although the rate of efflux of the mercury may be uniform, and the volume of the sample increases at the same rate, the gas collected in the tube is under a reduced pressure that increases as the tube empties. Thus the quantity of gas collected, as distinct from its volume, accumulates at an increasing rate towards the end of the sampling period, and an error comparable with that given by the plain sample tube may be introduced.

It has been suggested²⁵ that this defect of the Huntly tube can be compensated for by leading the mercury outlet tube down to the bottom of a specially shaped collecting cup flared towards the top, so that the tube dips below the surface of the mercury. As the mercury flows into the cup the back pressure due to the rising mercury opposes the efflux of the mercury in such a way as to regulate the pressure under which the sample is accumulating.

Tubes of the Huntly type are usually used with mercury as the confining liquid because the gas, as it collects, is scrubbed by the confining liquid. An apparatus has been described²⁶ in which the collecting tube is enclosed in another tube arranged so that the gas bubbles through only a small fraction of the confining liquid. An oil film keeps the main bulk of the liquid out of contact with the gases.

Sampling tubes of the Huntly type can be elaborated indefinitely to meet the criticisms that can be made of them, but, on the whole, they do not offer advantages that greatly outweigh the advantages of simpler arrangements.

Another apparatus for sampling gases at a constant rate has been described²⁷ in which the gas sample is taken over mercury in a plain sample tube. The mercury displaced passes through a fine capillary, whose resistance determines the rate of sampling, to a reservoir suspended on a spring, the characteristics of the spring having been chosen and adjusted so that, as the weight of the displaced mercury increases, the spring is extended and lowers the reservoir by the amount required to keep the head of mercury constant.

An apparatus for taking gas samples at a constant rate and one that has the advantage that it can be assembled from simple laboratory equipment was described by Gray¹⁴ and is shown in Fig. 10. This apparatus, although it is at first sight complex, is really simple and can be made in a compact form. Gas is drawn through the apparatus by the filter pump, A. The sample collects in the sample tube, B, as the confining liquid flows through the reservoir, C, which is counterpoised by the float, D. This reservoir is lowered at a constant rate that can be varied at will by controlling the flow of water from the constant-head device, E, through the nozzle, F, into the vessel, G. The vessel, H, is an excess vacuum relief.

The duration of sampling may be varied in several ways: (a) by choosing a nozzle, F, that delivers water at a suitable rate; (b) by adjusting the head

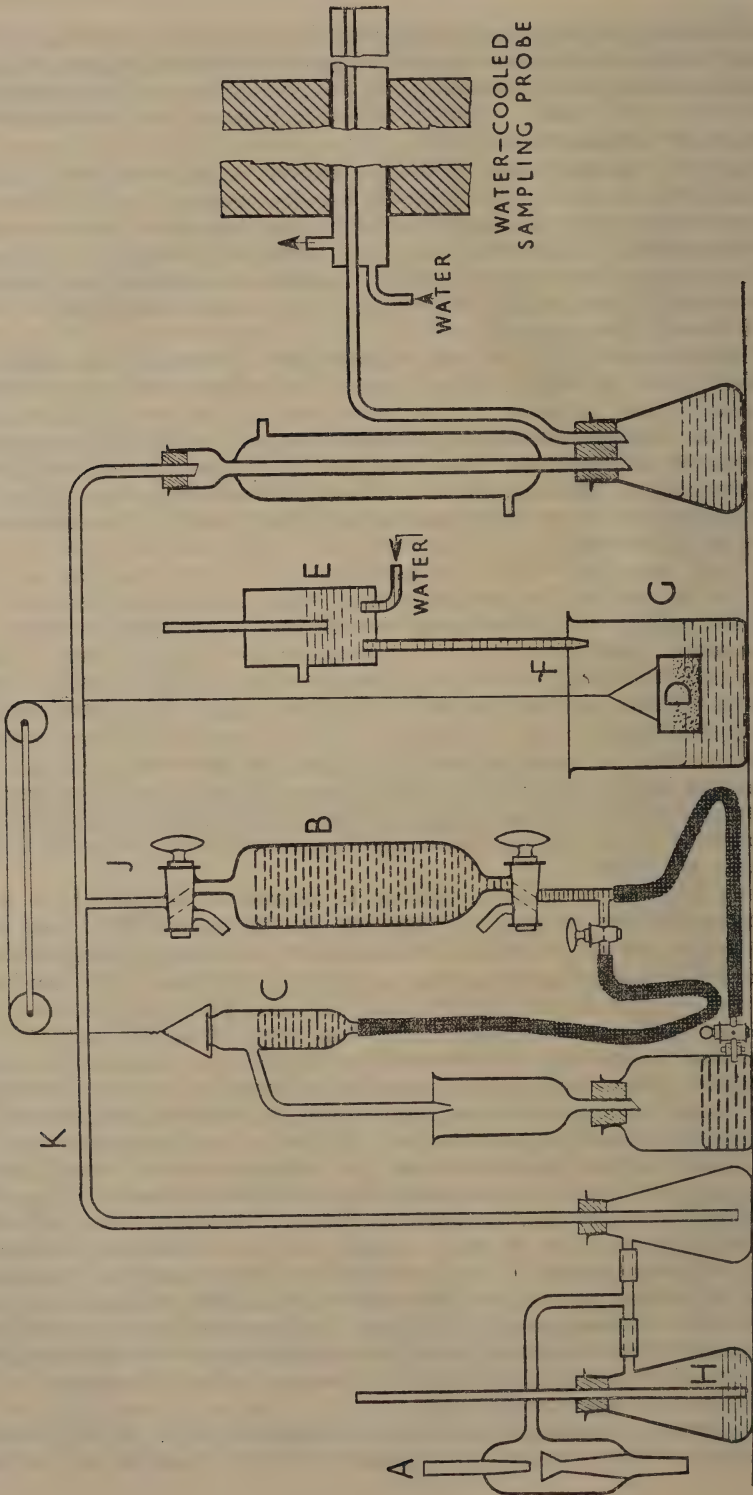


Fig. 10. Gray's gas sampling apparatus.

of water in E; (c) by choosing a vessel, G, of a suitable diameter; and (d) by selecting a sample tube, B, of appropriate length.

It has been a common practice to lower the reservoir, C, by means of a string passing round a drum driven electrically or by clockwork.

The connection, J, should be made of fine capillary tubing and should be long enough to ensure that there is no diffusion of gas back from the sample tube, B, into the sampling pipe, K.

"Breathing" through the sample tube connection. A fine capillary will hinder interchange by diffusion between the slowly accumulating sample and the gas in the sampling pipe. However, if the pressure in the sampling pipe falls, a fraction of the sample already collected proportional to the ratio of the initial and final pressures is expelled to the sampling pipe; or, if the pressure in the sampling pipe increases an unwanted increment is added to the sample. In practice such a tidal interchange between the sample tube and the sampling pipe may take place continually while the sample is being collected. It is not enough to place a non-return valve or a mercury seal between the sampling pipe and the sample tube; the breathing effect works both ways. A non-return valve would indeed prevent the loss of gas already collected if the pressure in the sampling pipe should fall, but it would also interrupt the collection of the sample until either the pressure rose again or until the sampling apparatus was re-adjusted. A non-return valve would prevent the tidal interchange, but the gas would be sampled only at the peaks of the pressure fluctuations or pulsations.

Irregularity in the rate of accumulation of the sample could also be caused by pressure changes due to variations in temperature, and, therefore, the position chosen for the sampling apparatus should be one where the temperature is reasonably constant.

When the pressure of the gas being sampled fluctuates, or when a pump introduces pulsations, it may be necessary to instal a pressure governor in the sampling pipe, and, if necessary, a suitable fan on the upstream side of the tee-connexion to the sample tube. Pulsations too rapid for the governor to eliminate should be suppressed by means of suitable reservoirs, and restrictions that will offer some resistance to movement of the gas.

An easily assembled portable apparatus has been devised by Pexton and Hutchison²⁸ for collecting a gas sample over mercury at a rate which is practically uniform. It is an arrangement of glass vessels and tubes. The confining liquid, mercury, as it flows out of the sample tube displaces water through a length of capillary tubing and through a mercury seal arranged in such a way as to maintain a constant differential pressure across the capillary. The sampling rate can be controlled over a wide range by replacing the capillary tube by another of different length or bore. By using a length of thermometer tubing a rate as low as 200 ml. in 48 hours was attained.

An apparatus of similar type has been described by Duke²⁹. Mercury as it flows from the sample tube displaces water through a capillary tube to issue from a nozzle below a sintered glass diaphragm that will pass water but be impervious to mercury at the working pressure. The sampling rate can be adjusted by altering the quantity of mercury in the regulator. A sampling rate as low as 150 ml. in a day has been attained.

Variable rates of flow. A principle for taking an average sample of a variable flow of gas consists in keeping the rate of sampling proportional to the rate of flow in the main stream, by taking the sample through a pin-hole orifice and keeping the differential pressure across the pin-hole the same as that across an orifice or venturi in the main.

A method of doing this has been suggested by Blackie³⁰. The sample,

after passing through the metering pin-hole, accumulates under a liquid-sealed bell enclosed in a gas-tight vessel. As it is essential that the gas outside the bell should be at the same pressure as that inside the bell, the bell must be delicately and accurately counterpoised in such a way as to compensate for the change in apparent weight of the bell as the immersion alters.

A sampling apparatus that maintains a constant sampling ratio, however the rate of flow in the main varies, has been described by Reeves³¹. The essential features are shown in Fig. 11. The apparatus consists of two drums: the upper drum is arranged as a Mariotte bottle, and the sample is collected in it over brine; the lower drum is a closed tank to receive the brine displaced

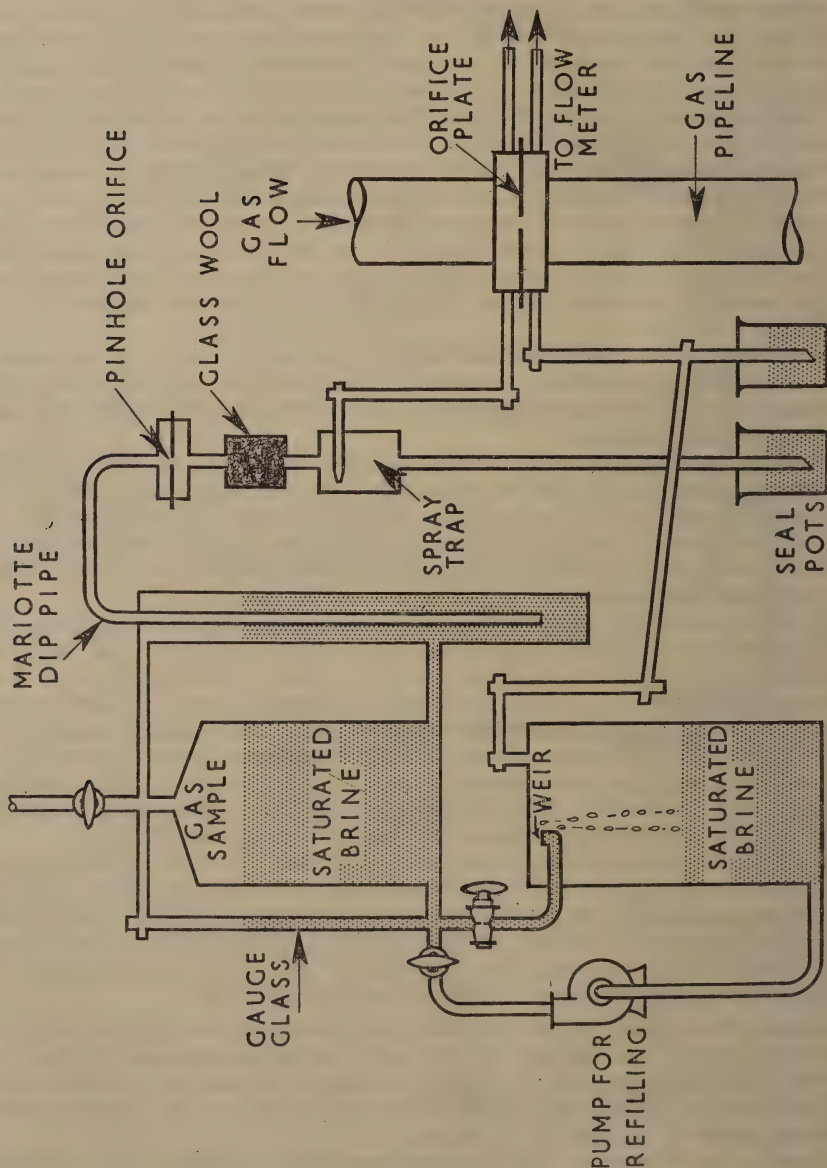


Fig. 11. Reeves' gas sampling apparatus.

from the upper drum. In Fig. 11 the dip pipe has been drawn in a separate side tube, thus applying Krah's method²⁶ of limiting the scrubbing action of the confining liquid as far as possible.

The sample, taken from the upstream tapping of an orifice in the main, is passed through a small orifice which controls the rate of sampling, to the dip pipe associated with the upper drum. The downstream pressure tapping of the orifice in the main is connected to the space above the brine in the lower tank.

The lower end of the dip pipe is on the same horizontal level as the weir over which the brine flows in passing from the upper drum to the lower one, and it can be seen that the sample collects at a rate that is a constant fraction of the main flow, and is independent of the absolute pressure in the main. Errors due to "breathing" do not arise.

The Reeves apparatus can be made of any size: for example, it might consist of two 40-gallon drums with brine as the confining liquid, or it might be made from a Huntly gas sample tube and used with mercury.

An apparatus for sampling at a variable rate has been described³² in which the gas is collected in a water-filled sample-holder by the displacement of water. The water flows out of the sample-holder at a rate controlled by the difference in pressure across an orifice plate in the main from which the sample is drawn: the pressure in the duct upstream from the orifice plate is applied directly to the gas space in the sample holder; the pressure tapping from the downstream side of the orifice plate is connected to the inside of a hollow float resting on the water in the sample holder. The pressures outside and inside the float are therefore respectively those upstream and downstream from the orifice plate; an arrangement of tubes allows water to flow, under the difference in these pressures, from the holder into the float and then out of the system. This makes way for the collection of a gas sample at a rate proportional to the rate of flow in the main. In order that the water in the sample holder shall present as little surface as possible to the gas collected over it, the float is designed so that it covers the whole surface of the water except for that exposed by the minimum clearance necessary between the float and the walls of the sample holder.

It would not be difficult to devise a sampling system in which the rate of withdrawal of the sample would be controlled through a suitable servo-mechanism operating the speed regulator of a motor-driven aspirator so as to keep the pressure difference across an orifice in the sampling pipe at all times equal to that across an orifice in the main. Such elaboration might be justifiable in a permanent installation where a widely fluctuating flow must be sampled accurately.

In another system³³ the main flow of gas passes through a gas meter which is coupled to a small sample meter and controls the speed at which it revolves, without actually driving it. Gas tapped off from the inlet of the main meter is passed through the sample meter and constitutes the sample. It is necessary to select a sampling meter with the appropriate characteristics: so that, for a given change in the differential pressure, the rates of flow through the two meters shall be in unvarying ratio to each other; there is then no strain on the coupling. This arrangement has been used successfully to sample coal gas flowing at a rate varying between 4,000 and 7,000 cubic feet per hour, with the pressure in the main varying between six and 10 inches of water, and with the sample being discharged into a gas-holder against a back pressure varying between $2\frac{1}{2}$ and $4\frac{1}{2}$ inches of water. A sampling ratio of one to 500 was maintained to within 0.3 per cent.

It would be easy to adapt this two-meter system so as to avoid having to

find two meters with their characteristics related in the special manner essential when the two meters are linked by a chain. The meter in the main gas stream could be arranged to close an electrical relay contact or micro-switch once per revolution of one of the spindles of the counting mechanism, and thereby operate an electro-magnetic valve that would permit the sample meter to turn once and then stop. Such an arrangement would be at its best with a sample meter small enough to be switched in frequently. The sampling would not be theoretically perfect, but in practice it would be nearer to the ideal than much sampling as normally done.

Snap samples to represent the average. A quantity of gas can be satisfactorily represented by a sample made up of a large number of snap samples taken at equal intervals of time. The analysis of a sample composed of equal volumes of the component snap samples will give the arithmetical mean, whereas, if the volume of each snap sample is proportional to the quantity of gas it represents, the combined sample will be a true average sample.

The order of magnitude of the error introduced by taking the arithmetical mean instead of the true average can be estimated by comparing the calculated values of the mean and average carbon dioxide contents of the flue gases from a hypothetical furnace.

The volume of flue gas from a given weight of coal is almost exactly proportional to the ratio that the maximum carbon dioxide content theoretically possible bears to the observed carbon dioxide content; thus the rate of flow of the flue gases can be determined when the carbon dioxide content of the waste gases and the rate at which the fuel is burning are both known.

Now, however the carbon dioxide content of the flue gas varies, the variation may theoretically be represented by a combination of sine curves. Imagine, then, that coal is being burnt at a constant rate in a furnace, and that the carbon dioxide content of the flue gases varies sinusoidally over the firing cycle.

Under these conditions it can be shown that the error introduced by taking the mean instead of the true average will depend on the percentage variation from the mean, and not on the actual value of the mean. The following table gives a specific example; the last two columns express the general result. The true average will always be less than the mean.

TABLE 1
PROBABLE MAXIMUM ERROR DUE TO TAKING THE
MEAN ANALYSIS INSTEAD OF THE AVERAGE

Carbon dioxide content				Variation about the mean. Per cent. of the mean	Difference between mean and average. Per cent. of average
Minimum. Per cent.	Maximum. Per cent.	Mean. Per cent.	Average. Per cent.		
9	11	10	9.95	10	0.5
8	12	10	9.80	20	2.1
7	13	10	9.54	30	4.8
6	14	10	9.16	40	9.2
5	15	10	8.66	50	15.5
4	16	10	8.00	60	25.0
3	17	10	7.14	70	40.1
2	18	10	6.00	80	66.7

The errors indicated in the table may be regarded as maxima: for, if the rate at which the fuel is burning varies, the rate at which carbon dioxide is evolved will vary correspondingly; and if the flow of air through the furnace is constant, the carbon dioxide content of the waste gases will vary in a manner

directly related to the variations in the rate at which the fuel is burning. And if the air flow is constant the average carbon dioxide content of the flue gases will be almost identical with that given by the mean of a large number of equally spaced snap samples. That is, the error would be negligible.

In practice, however, the rate at which the fuel burns and the rate at which air is supplied to the furnace vary independently, and the error introduced by taking the mean instead of the average will lie between zero and the value as indicated in the table.

In a boiler trial the total volume of the flue gases is calculated from the weight of carbon burnt and the average carbon dioxide content of the flue gases. If the mean, instead of the average, is used in the calculation, the loss of sensible heat in the flue gases from a hand-fired furnace burning coal might be underestimated by about 10 per cent. of its value; and if the sensible heat loss is about 20 per cent. of the total heat, the heat balance would underestimate the flue loss by about 2 per cent., and over-estimate the "radiation and unaccounted for" loss by the same amount.

The smaller the fluctuations in the carbon dioxide content of the flue gases the less the error. The example considered might represent the case of a hand-fired furnace burning coal, and might be regarded as the upper limit of error for good practice.

Whether a quantity of gas can be adequately represented by a series of snap samples, and whether the arithmetical mean may be taken instead of the true average are best decided by considering the specific problem.

Snap samples to represent the mean. An example of the manner in which the carbon dioxide content of a flue gas may vary in practice is shown in Fig. 12 for a hand-fired marine boiler operating with natural draught. Snap

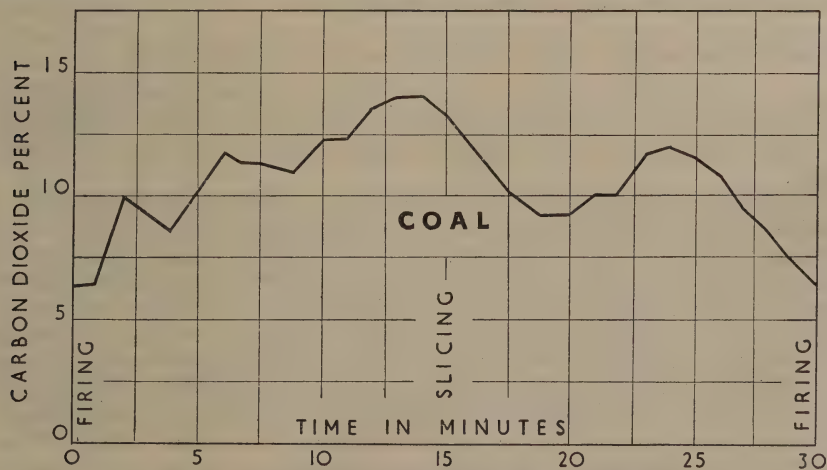


FIG. 12. Effect of variations in combustion conditions on composition of snap samples of flue gas.

samples were taken at intervals of one minute, and were analysed for carbon dioxide. The results show a cyclic variation over the 30-minute periods from one firing to the next.

In this example, if only one sample had been taken to represent the cycle, it would have given a carbon dioxide content lying between 6.2 and 14.1 per cent. If any two snap samples had been taken with an interval of 15 minutes, the fifteen possible means of their carbon dioxide contents would have ranged from 8.8 to 12.0.

It is clear that, as the number of snap samples is increased, the possible range of the mean of their analyses converges to the mean of the analyses of all thirty samples. In this example the mean carbon dioxide content of any ten equally spaced snap samples would lie between 10.4 and 10.8 per cent., and this range might be regarded as sufficiently narrow to represent the gas as a whole.

If an analysis is required to represent an eight-hour shift made up of similar 30-minute cycles, the samples should be taken not only equally spaced throughout the shift, but also equally spaced in the cycle, all the cycles being considered as one. In the example considered both conditions are complied with if 11 samples are taken, provided that the individual cycles are fairly similar. Ten, or more so eight or 16, equally spaced throughout the shift, might give some coincident spacing within the cycles. The number of cycles and the number of samples should be prime to each other, as, for instance, when $n + 1$ equally spaced samples are taken from n consecutive cycles.

Average sample by increments. In some instances it might be good enough to take into the sample tube measured increments at predetermined time intervals, the sample tube being shut off between the times when the increments are collected. Accurate timing is important and it would be advantageous to make use of an interval timer set to ring a bell at the required time. If the sampling apparatus can be visited only at irregular intervals, a sample should be set to collect at about the correct rate, judged by the dripping of the mercury from the sample tube. Then at each visit to the apparatus, the operator would transfer to another sample tube a volume taken from the primary sample proportional to the time that has elapsed or to the volume that has passed since the last transfer. The primary sample tube would then be refilled with mercury and sampling re-started.

THE STORAGE AND TRANSPORTATION OF GAS SAMPLES

It is often necessary to store a gas sample for some time before it is analysed or to transport it from its place of origin to the place where it is examined and these conditions call for special considerations that are not always applied.

However a gas may have been sampled in the first place, the sample, or a portion of it, intended for analysis is preferably contained in a tube of the form shown in Fig. 8. The tube should be examined closely before use for defects. The inlet capillaries should be clear and the cocks should be properly greased; proprietary stopper greases, of which there are summer and winter grades, can be bought, and it should always be realized, whether the grease is bought or home made, that it must have the right physical properties; when the cocks are greased with the minimum adequate quantity of the stopper grease, the cock, viewed through the barrel, should be clear, transparent and not streaky. Gas samples can be stored indefinitely in sound tubes without undergoing any change in composition, even though extremes of atmospheric temperature, and consequently fluctuations of pressure in the sample of the gas in the sample tube, may be experienced.

A gas sample taken in or transferred to a sample tube should be introduced into the tube in such a way that it is under a pressure slightly above the atmospheric. If there should be a leak, it will then be outward and not inward, and so guard against the possibility of contamination due to a leakage of air into the sample. On the other hand this safeguard should not be allowed to engender a false sense of security. If the cocks are not gas-tight the excess pressure will soon be dissipated and the sample may be contaminated if the analysis of the sample is delayed.

The plug of a cock must be held in the barrel of the cock by means of wire or string so that it cannot be shaken out. Whereas a rubber band is convenient for this purpose, there is a danger, if it is not adjusted properly, that it may turn the cock on; it is better not to use a rubber band if this risk cannot with certainty be avoided.

When samples of gas taken over mercury, have to be transported no mercury should be left in the tube; if a sample tube containing some mercury is subjected to violent movements the impact of the mercury on the walls of the tube can easily break the tube.

Usually when gas samples are to be transported it will be desired to send a number of samples. A wooden case can readily be made to hold a number of sample tubes in padded compartments in which the tubes are clipped with wooden turn-buttons. The tubes must be held so that they cannot rattle laterally or slide longitudinally in their racks and they must be clipped in position with no strain on the glass. The weakest part of a tube is obviously at the neck between the cock and the bulb; care must be taken that this part is supported without strain and is not endangered by a blow on the tube or the cock itself.

Contamination of samples. The leaking of air into gas samples, whether at the time when the sample is taken or while it is being stored or transported, has already been dealt with. It is well to emphasize that, if the sampling system is at all times at a pressure above the atmospheric, leakage can only be outward, with no detriment to the sample.

Sometimes the volume of the sample must be such that a small gas-holder is used to collect it. The crown of the holder inevitably contains the residue of the previous sample. This can be reduced to a negligible fraction of the volume of the sample by raising the water level in the holder tank to cover the crown of the holder. The stand pipes inside the holder must be lengthened so that they extend above the new water level, small domes being provided in the crown of the holder to accommodate the ends of the pipes.

Water or an aqueous salt solution that has been used in collecting a previous gas sample and that has been saturated with that gas will contaminate a sample of a different gas taken over it by giving up some of the dissolved gas to the new gas; and the fact that the confining liquid is saturated with the previous gas sample may not prevent some constituent in the new gas sample from being dissolved preferentially. Such an aqueous confining liquid can also bring about a change in the composition of a gas sample, with which it has been saturated, if the pressure of the gas stored over it is altered; a change in the partial pressure of some more soluble constituents of the gas will cause the release from solution or the loss by solution of some of that constituent, according to whether the pressure is reduced or increased.

It may not be possible to avoid these effects completely, but they should be borne in mind and every attempt made to minimize them.

CONCLUSION

An attempt has been made to consider comprehensively, though not exhaustively, the circumstances relating to the sampling of gases, and to throw those of practical value into relief and drive into the background many somewhat specious points frequently discussed. It is hoped that some points that are often indecisively argued about have been disposed of, as far as the present state of knowledge and the devices hitherto made available permit.

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CHAPTER 30

ANALYSIS OF FUELS

SOLID FUELS

A KNOWLEDGE of the properties of solid fuel is necessary for its efficient utilization and for the maintenance of control over successive deliveries. This knowledge is obtainable in part by the application of special methods of analysis; further tests, generally of an empirical character, are also necessary in order to assess certain properties of coal not disclosed by analysis but of importance in relation to the purpose for which the coal is used.

Since coal is a complex and heterogeneous substance it has been necessary to prescribe methods of analysis and test in strict detail. If the interpretation of the results is to be of value to the user it is particularly important that the empirical methods be adhered to rigidly. Methods have been standardized by the British Standards Institution and the specification B.S.1016 (which contains methods for the analysis of coke also) should be followed in all coal examination.¹ The methods given in the specification are strictly formal; fuller explanatory details of the methods are contained in Fuel Research Survey Paper 44². Revised methods for the analysis of coal ash and coke ash are given in Fuel Research Survey Paper 50³.

The scale on which coal is used varies widely and small-scale users will not normally have to carry out all the analyses specified. In large-scale usage, or in performance tests, analytical control may be more rigorous. In certain industrial uses particular emphasis may be placed upon one or other of the empirical tests; for example, the caking power of the coal is of special importance to producers of metallurgical coke.

The condition or state of the coal or coke as used has an important bearing upon its suitability for the purpose intended and upon its efficient use. In the examination of solid fuel, therefore, for any given purpose, or in the examination of a consignment of solid fuel, an exact statement should be made of the size distribution and of the moisture content at the time of usage or, in the export market, at the time of weighing for sale. The method of taking a sample for such purposes is described in Chapter 29 and differs from the method of taking a sample for analysis.

The National Coal Board has adopted the Report⁴ of the Coal Grading Committee on the Size Grading of British Coals published by the British Colliery Owners' Research Association. The essentials of the classification of the sizes of coals are (a) the definition of large coals by the type and sizes of the screens over which they are produced, (b) the adoption of seven sized grades, specifying upper and lower limits of screen sizes to conform to a standard nomenclature and with two criteria of under-size and (c) the description and method of treatment of smalls, i.e. whether untreated, washed or dry-cleaned, with a specification of the upper limit of size and the percentage passing through an $\frac{1}{8}$ in. mesh British Standard sieve.

It may be noted that a round hole of x in. diameter is approximately equivalent to a square hole having an aperture of $\frac{7}{8}x$ inch. (See also Chap. 2, The Size of Coal.)

In good practice the average product from a colliery will not contain more than one-half of the maximum permitted content of undersize material. The description of small coals must include the method of preparation and the exact size, with an attached figure giving the proportion which will pass a

STANDARD SIZE GROUPS FOR GRADED COAL

All sizes are given in inches

Name of Group	Round-hole sizes			Maximum permitted percentage content of undersize passing a square aperture of								
	Typical screen	Permitted range of screen apertures										
	size	Upper limit	Lower limit	1½	7⁄8	¾	½	⅜	¼	⅛	1⁄16	1⁄32
Large cobbles	6×3	6 — 8	3 — 5	—	—	—	—	—	—	—	—	—
Cobbles ..	4×2	4 — 5	2 — 3	—	—	—	—	—	—	—	—	—
Trebles ..	3×2	2½ — 3½	1½ — 2	15	—	—	2	—	—	—	—	—
Doubles ..	2×1	1½ — 2½	1 — 1½	—	25	—	—	3	—	—	—	—
Singles.. ..	1×½	1 — 1½	½ — 1	—	—	20	—	—	3	—	—	—
Peas	½×¼	½ — ¾	¼ — ½	—	—	—	—	15	—	3	—	—
Grains	¼×⅛	¼ — 7⁄16	⅛ — ¼	—	—	—	—	—	25	—	—	3

square aperture of 1⁄8 in., e.g. smalls, washed, 1 in 50 (2 per cent.). The percentage figure indicates the fines content which is not exceeded more than once in 20 consignments.

MOISTURE

Moisture in coal is comparable to ash content in reducing the fuel value of the coal, not only in direct proportion by taking the place of coal, but additionally on account of the latent heat of evaporation during combustion of the coal; in furnace operations it may also lower the working flame temperature. Its exact measurement in the consignment of coal as delivered, or in the coal as used is, therefore, of the greatest importance. It is specified in B.S. 1016 that a special sample should be taken for moisture content only. This is taken under conditions that avoid loss of moisture during handling and may involve air-drying in order that the sample sent to the laboratory shall not be visibly wet. The label on such a sample should clearly show the loss of moisture on air-drying so that when the moisture content is determined in the laboratory the moisture content at the time of sampling can be calculated. This may be the moisture content as used in an industrial operation or the moisture content as shipped for transport. If moisture determinations are made later in the laboratory this correction to the original moisture content of the coal should be carefully indicated in setting out the results.

PROXIMATE ANALYSIS

Moisture and ash contents are almost invariably determined, since these are the so-called “inerts”. It is usually desirable, however, even in a simple scheme of analysis, to determine the volatile matter content also. The difference between 100 per cent. and the sum of the percentages of moisture, ash and volatile matter, is referred to as the “fixed carbon”. The statement of the analysis of a coal in terms of these four items is described as the “proximate analysis”. Determinations are made on a sample ground to pass a 72-mesh B.S. sieve and air-dried to a condition of near-equilibrium with the laboratory or balance room atmosphere.

Moisture is determined under controlled conditions by drying 1 g. of the coal to constant weight. This moisture is normally referred to as moisture in the air-dried coal, but it would have greater significance if the air-drying of the coal were carried out at a constant temperature and constant relative humidity. It would then have a value bearing some relation to the rank of

the coal and could be interpreted in relation to the corresponding values for other coals. This proposal is now in process of standardization.

Ash content is determined on the air-dried coal by burning 1 g. completely to ash under controlled conditions. This ash is the fully oxidised residue of the mineral matter originally in the coal and is nearly always less in amount than the original mineral matter, through the loss of water of hydration of clays or of carbon dioxide, or by oxidation of iron sulphide. The relation between the ash derived from a coal and the mineral matter originally present in the coal is discussed more fully in Chapter 2, where the formula for conversion, in the case of British coals, is given.

The determination of *Volatile Matter* is an empirical test and if reliable and comparable results are to be obtained, close adherence to the prescribed standard conditions is imperative. One gram of the sample is heated in a silica crucible at 925°C. for 7 minutes under exactly controlled conditions and the loss of weight, with due correction for moisture content, is recorded as "volatile matter".

ULTIMATE ANALYSIS

The ultimate analysis refers to the exact measurement of the elements of carbon, hydrogen, nitrogen and sulphur in solid fuel.

The precise methods given in B.S.1016 demand a higher level of analytical skill than the more empirical methods of proximate analysis.

If the proportions of the elements are calculated on a mineral-matter-free basis, the difference of their sum from 100 per cent. represents the oxygen content of the coal. There is, as yet, no reliable method for the *direct* determination of this oxygen. Oxygen content may alternatively be ascertained by calculating the results on a dry ash-free basis, and again deducting the sum from 100 per cent. This figure for oxygen is in error in proportion to the difference between mineral matter and ash.

Carbon and Hydrogen. In the determination of carbon and hydrogen a weighed quantity of coal is burned completely in oxygen at 800°C., the products of combustion being passed over heated copper oxide to oxidise them fully to carbon dioxide and water. Oxides of sulphur are removed by passage over heated lead chromate, and a silver gauze spiral takes up any chlorine present. The gases are then passed through two weighed vessels containing suitable absorbents, e.g. calcium chloride and caustic alkali, to collect the carbon dioxide and water. The amounts of carbon and hydrogen present are then calculated from the increases in weight of the absorbents.

In an alternative method, the coal is burned in oxygen at 1,350°C. The combustion train is simpler and the method has the advantage of effecting much saving of time.

Nitrogen. The nitrogen content of coal is determined by the Kjeldahl method, in which 0.1 g. is decomposed by boiling sulphuric acid containing a catalyst. The nitrogen is converted to ammonia, which forms ammonium sulphate with the acid. Subsequently the ammonia is set free by the addition of alkali and "steam distilled" into a known amount of standard acid. Titration of the excess acid gives the equivalent amount of ammonia and hence the nitrogen content.

Sulphur. The total sulphur in coal may be determined by heating a weighed quantity (1 g.) well mixed with Eschka mixture (one part by weight of anhydrous sodium carbonate and two parts of light magnesium oxide) until all the carbonaceous matter has been burned off. The sulphur is retained by the Eschka mixture, from which it is subsequently removed as a soluble sulphate, precipitated as barium sulphate and weighed as such. An alternative method

is to burn 0.5g. of the coal in oxygen at $1,350^{\circ}\text{C}$. and absorb the products of combustion in a hydrogen peroxide solution. The sulphuric acid absorbed is determined volumetrically.

Sulphur may be present in coal in any of three forms; as sulphate, pyrites or organic sulphur. Organic sulphur is associated with the coal substance but pyritic sulphur is largely adventitious and may be removed by cleaning processes.

OTHER ELEMENTS

Although the ultimate analysis defines the proportions of the main constituents of a fuel, there may be other elements, present which could have an important bearing on the suitability of the fuel for special purposes. The most important of these are chlorine, phosphorus and arsenic.

Chlorine. The coal is heated with Eschka mixture at 675°C . until all the organic matter is destroyed. The residue is extracted with water and a measured excess of silver nitrate added to the extract. The amount of silver nitrate remaining is determined and hence the amount used, from which the chlorine content of the coal can be calculated.

Phosphorus. The ash obtained in the proximate analysis is broken down by treatment with nitric and hydrofluoric acids, and the phosphorous extracted and precipitated, under strictly controlled conditions, as ammonium phosphomolybdate. This is dissolved in an excess of standard sodium hydroxide solution and the amount of alkali remaining titrated with nitric acid. Normally the phosphorus content is between 0.005 and 0.1 per cent.

CHLORINE AND PHOSPHORUS

Alternative methods for determining chlorine and phosphorus at high temperature are also prescribed.

Arsenic. Arsenic is present in British coals in very small quantities, usually not above 10 parts per million. Its determination is important in respect of coal or coke used in the manufacture of foodstuffs or beer. These have to conform to a strict specification for arsenic content (about 5 parts per million to 0.005 per cent.). To determine the arsenic content, the coal is mixed with lime (or magnesia) and heated to destroy the organic matter, when the arsenic is retained by the lime. Arsenic is regenerated from the residue as the gas arsine, the amount being determined either by the colorimetric measurement of "molybdenum blue" or (up to 6 p.p.m.) by absorption on a paper disc on which a characteristic stain is developed.

CALORIFIC VALUE

The calorific value is a very important characteristic of a fuel, for it expresses the amount of heat generated by a complete combustion of unit weight of fuel.

The determination requires special apparatus and a standardized procedure. It is a skilled laboratory operation in which an accurate weight of fuel (about one gram) is burned in an atmosphere of compressed oxygen in a "calorimetric bomb" immersed in water, the temperature rise of the water being measured with extreme accuracy.

The laboratory determination of C.V. gives a measure of the amount of heat liberated in a calorimeter "bomb" under defined conditions, the result being recorded as the *Gross Calorific Value at Constant Volume*. When coal is burnt for industrial purposes no element of pressure within a container (such as the bomb) is involved; the operative C.V. is the *C.V. at constant*

pressure. The difference between the two is of the order of 1 part in 1,000 for most bituminous coals and 0.5 part in 1,000 for anthracite. Since the accuracy of a laboratory determination of C.V. is usually of the order of ± 2 parts in 1,000, the difference between the two values may be ignored.

The gross C.V. includes the heat of condensation of the water vapour produced in the combustion by cooling to 60° F. This amounts to 1,055 B.t.u./lb. and this should be deducted to obtain the *net calorific value*. The Net Calorific Value is a truer measure of the heat made available when the fuel is burned industrially, but it is more usual to quote the gross value.

The gross calorific values of normal commercial grades of British coals range from about 9,000 to 15,000 B.t.u. per lb., depending on the rank of the coal and the percentage of inerts (moisture and ash) present.

The figure obtained in the determination of C.V. at any particular laboratory temperature will be higher than that obtained at a higher temperature. The standard temperature for the laboratory determination is 25° C.

The calorific value can be calculated from the ultimate analysis by the formula: Gross c.v. (cal./g.) =

$$\left[C \times 8,137 + \left(H - \frac{O + N - 1}{8} \right) \times 34,500 + S \times 2,200 - H_2O \times 600 \right] \div 100$$

where C, H, O, N, S and H₂O are the percentage of carbon, hydrogen, oxygen, nitrogen, sulphur and moisture, respectively, in the coal.

CAKING PROPERTIES

The behaviour of a coal when it is heated has a marked effect on its performance in use and on its suitability for various purposes. For example, only those coals that give a hard dense coke when heated in the absence of air are suitable for making metallurgical coke. Coals of poorer caking property are necessary if a free-burning reactive coke is required. For many industrial and domestic uses feebly-caking or non-caking coals are often desirable. While many appliances can use coals with widely differing caking properties quite efficiently, the rates of throughput or rates of combustion of these various coals will often differ significantly because of their different caking properties.

It is, therefore, important when selecting coals for certain purposes or when judging the relative merits of different coals for use in the same appliance, to have a measure of the caking properties. Of the number of recognised laboratory tests each gives some measure of these but no one of them is all-embracing. It is, therefore, recommended that more than one of the recognised laboratory tests be used and supplemented by careful observation of the behaviour of the coal in use.

The tests in common use in Great Britain are :

- (a) The British Standard Crucible Swelling Test (Crucible Swelling Number).
- (b) The Gray-King Coke Type Assay at 600° C.

Each of these is an empirical test; great care must, therefore, be taken to carry out the method exactly as described by the author. (See Figs. 1, 2, Chap. 2.)

(a) The British Standard Crucible Swelling Test.

One gram of coal ground to pass a 72-mesh B.S. test sieve is heated in a standard crucible for not less than 2½ minutes up to a temperature of 820° C. The method and rate of heating are defined. The profile of the coke residue is matched against standards (B.S. 1016, Pt. 12, Fig. 3). British coals are classified into groups designated by the numbers ½ to 9, in units of 0.5. The number thus allotted to the coal is known as the *Swelling Number*.

(b) *The Gray-King. ~~Low~~ Coke Type Assay.*

The coke produced when 20 g. of coal ground to pass a 72-mesh B.S. sieve are carbonized under standard conditions to a final temperature of 600° C. is defined by its size and appearance, if the coal is non-swelling. If the coal is swelling the coke is defined by the number of parts of electrode carbon powder in 20 parts of mixture that produces a "standard coke" which is hard and of the same volume as the original 20 g. of coal in the assay tube. There are 17 coke types, distinguished by letters.

Mineral Matter: Analysis of the Ash. Ash, as already defined, is the fully oxidised residue of the mineral matter originally present in the coal. When fully oxidised, the ash consists mainly of the oxides of aluminium, silicon, iron, calcium, magnesium and sulphur, with smaller amounts of the oxides of the alkalis, titanium, manganese and phosphorus. Some of these occur as sulphates, silicates and phosphates.

The complete analysis of a coal or coke ash is a lengthy and laborious procedure calling for considerable analytical skill and facilities for accurate work. A scheme of analysis has been worked out, on the basis of many years' experience in several laboratories. Full details are given in Fuel Research Survey Paper³ No. 50.

Some idea of the character of an ash can be deduced from its colour. It may be assumed, for instance, that in general a deep red ash has a high iron content and will fuse at a comparatively low temperature; a white ash with high silica and/or magnesia content will have a much higher fusion temperature. But it can be lower if calcium is present.

The fusion temperature of an ash is determined by observing, by means of an optical pyrometer or thermo-couple, the temperatures at which a triangular pyramid of the ash (a) first shows signs of deformation and (b) fuses completely into a "blob". The atmosphere in which the determination is carried out will affect the fusion temperature since if the atmosphere is a reducing one lower oxides will be formed, e.g. ferrous oxide, FeO, the lower oxide of iron, which will fuse at a lower temperature than the higher oxide Fe₂O₃. The conditions in which the fusion temperatures were determined must, therefore, be stated. Details of procedure are given in B.S. 1016.

METHOD OF REPORTING RESULTS

When setting out the results of analyses great care should be taken to indicate clearly the bases of reporting, i.e. whether the analyses are calculated on the coal "as received", "as used", air-dried, dry, dry ash-free, or dry mineral-matter-free.

An orderly and consistent method of reporting should be adopted. In this connection the reader is referred to the discussion on Reporting and Interpretation of Results of Analysis, Chapter 2 and B.S. 1016, Pt. 16.

LIQUID FUELS

The laboratory examination of fuel oils to ascertain how far they satisfy the criteria for satisfactory performance involves a wider range of analytical tests than is necessary in the case of coal. Most of these tests are empirical; that is, the numerical value of the result is dependent on the shape and dimensions of the apparatus used and the conditions of the test operational procedure. Consequently consistent and comparable data are obtainable only if all analysts conform strictly to the standardized apparatus and technique. In the British petroleum industry the standardized procedure is that laid down in very full detail by the Institute of Petroleum in the publication "Standard

Methods for Testing Petroleum"⁵, an essential part of the equipment of any laboratory engaged in testing oil fuels.

The criteria used to assess the suitability of fuel oils for their uses, or conditions of use, are discussed in Chapter 4, and the procedure for taking a representative sample for analysis in Chapter 29. In the following paragraphs the methods and apparatus used are briefly described. "Standard Methods for Testing Petroleum" must be consulted by anyone actually undertaking the work.

SPECIFIC GRAVITY

This is determined directly by using a hydrometer or gravimetrically by the well-known specific gravity bottle. Results are expressed as Sp. Gr. 60° F./60° F. It is necessary, therefore, either to make the determination at 60° F. (the preferable method) or to measure the temperature of the sample being tested and to apply the appropriate correction taken from the standard tables. This correction ranges from 0.00040 per deg. F. for kerosine, to 0.00036 for a heavy fuel oil or a creosote-pitch mixture.

VISCOSITY

The subject of viscosity is discussed in Chapter 10, to which the reader is referred. In testing fuel oils viscosity is measured by observing the number of seconds taken by 50 millimetres (ml.) of the oil to flow through a standard orifice in a viscometer of standard design at a specified temperature. The usual form of the Redwood Viscometer is the No. 1 type. It is used for oils with Redwood Viscosities from 30 seconds to 2,000 seconds. For more mobile oils a U-tube type of viscometer must be used; for more viscous oils the Redwood No. 2 Viscometer, which has a wider jet and gives a time of flow one-tenth that of the No. 1 viscometer is used. As the No. 2 instrument is rarely used, the following description relates only to the more common No. 1 form.

It consists of a metal cup surrounded by a heating bath and provided at the bottom with a drilled agate plug, the orifice of which is controlled by a ball valve. The oil cup is filled with the sample up to a fixed level, the temperature suitably and accurately adjusted and then the time taken for 50 mls. to flow from the cup into a graduated receiver is measured by a stop watch. The usual temperatures employed are 100° F. for diesel oils and 100° F. or 122° F. for furnace fuels. In Britain every Redwood viscometer is submitted to the National Physical Laboratory for checking before sale, and carries an N.P.L. certificate.

The Redwood apparatus has been largely replaced in recent years by the U-tube viscometer (described below) which gives kinematic viscosity in centistokes. The U-tube viscometer is preferred to the Redwood instrument because:

- (a) the apparatus is cheaper and more easily cleaned;
- (b) temperature control (the main difficulty in viscometry) is more accurate;
- (c) the amount of sample required for the test is much smaller;
- (d) the method is applicable to liquids of all viscosities if the appropriate viscometer is selected;
- (e) many specifications now state their requirements in centistokes.

The viscometer (of which there are several types) consists of a glass U-tube, the limbs being connected by a capillary tube. Five models of viscometer, differing mainly in the dimensions of the capillary, cover by steps the extensive range of 0.5 centistokes to 1,500 centistokes, but model 2 (6 to 75 cs.) and model 3 (50 to 300 cs.) cover the range of ordinary fuels. The principle of use of the U-tube viscometer is similar to that of the Redwood viscometer in that

the instrument, charged with the oil sample, is suspended in an accurately controlled thermostat and the time of flow of a definite volume of the oil measured. The instruments can be calibrated by using water or oils of known viscosity (obtainable from the National Physical Laboratory) or the calibration may be done at the N.P.L. The time of flow in seconds multiplied by the calibration constant of the instrument minus a design constant gives the kinematic viscosity in centistokes.

Viscosities in Redwood seconds can be converted into centistokes, or *vice versa*, by the use of the conversion table published in "Standard Methods".

The dynamic viscosity in centipoises can be obtained by multiplying the kinematic viscosity in centistokes by the specific gravity in c.q.s. units.

FLASH POINT

Abel Apparatus

This form of apparatus is used for determining the flash point of all petroleum products which flash below 120° F. Its dimensions are strictly defined and in Britain the instrument and its thermometers must be certified and stamped by the Board of Trade every ten years.

It consists of a test cup (the lid of which carries a thermometer) a test flame and (permissively) a stirrer. The whole is mounted in a water-bath with an annular air space between the two.

The oil cup is filled to a marked level with the oil to be tested and its temperature slowly raised by means of the water bath. The exact procedure, which must be rigidly followed, depends on whether the oil flashes above or below 90° F. At regular specified intervals the test flame is applied by a sliding mechanism to the interior of the test cup through an aperture opened by this mechanism and the temperature of the oil when such an application produces a "flash" in the vapour space is recorded as the Flash point (Abel).

Pensky-Martens Apparatus

This apparatus is used when flash points above 120°F. are to be determined: that is, for the majority of fuel oils. The apparatus is similar in principle to the Abel apparatus, though of different design and dimensions, and heated by means of an air-bath and stove. The stirrer stirs both the oil and the vapour space. All details of design and dimensions as well as procedure must be rigidly adhered to.

The oil-cup is filled to a marked level, heated at a rate of 10° F. per minute and stirred at 1 revolution per second. The test flame is applied to the vapour space at each 2° F reading until a flash is observed. As the small amounts of water sometimes present in fuel oils affect the flash point the sample must be dried, if necessary, by a suitable dehydrating agent such as calcium chloride.

The flash point so determined is known as a "closed" flash point. If the test is conducted without the cup being covered an "open" flash point is recorded, usually some 30 or 40 degrees higher. Open flash points are often determined for lubricating oils but not for fuels.

POUR POINT

This is the lowest temperature at which the oil will pour or flow when chilled without disturbance under prescribed conditions.

The apparatus consists of a test tube $1\frac{1}{4}$ inches in diameter carrying a thermometer and mounted in a wider tube (to provide an air-space) which in turn is immersed in ice-water or freezing mixtures according to the pour point of the oil.

The oil sample is placed in the test tube and warmed to 115° F. to ensure that any wax crystals are dissolved. It is then slowly cooled and at intervals of 5° F. the tube is removed from the cooling bath and held gently tilted. Ultimately a point is reached when the tube can be held horizontally for five seconds without any movement of the oil. The pour point is taken as the temperature 5° F. above this point of solidification.

CALORIFIC VALUE AND SULPHUR CONTENT

As these two tests are made in the same apparatus, usually at the same time, they may conveniently be described together. The principle is simple though the apparatus is somewhat complicated and costly.

A weighed amount (about 1 g.) of the oil contained in a small platinum or silica crucible, is placed in a stainless steel 'calorimetric bomb' in such a way that the bomb can be charged with compressed oxygen and the oil ignited electrically. The quantity of oxygen used is ample to burn the oil completely, the sulphur in the oil being converted into sulphuric acid.

If the calorific value is to be determined the bomb is submerged in a large water calorimeter mechanically stirred and provided with a very sensitive thermometer recording the temperature of the water before and after the combustion of the oil. Suitable corrections having been applied for the water-equivalents of the bomb and calorimeter vessel and for temperature changes due to radiation, calculation gives the gross calorific value of the oil. If the net calorific value is to be determined experimentally the products of combustion must be expelled from the bomb by a current of dry air and the water produced absorbed in a weighed calcium chloride tube. This is not, however, commonly done.

An alternative method extensively used for determining the sulphur content of petrol, kerosine and vaporising oil is the 'lamp method,' in which a known weight of the oil is burned in a current of purified air and the products of combustion are aspirated through an alkaline solution, the sulphur being finally estimated as sulphuric acid by volumetric or gravimetric methods.

If sulphur content is to be determined a little water (2 ml.) is also placed in the bomb to ensure the absorption of all oxides of sulphur. The calorimetric observations are, of course, not taken if only sulphur content is to be determined. After combustion the bomb is opened, the contents are washed out, bromine water is added to convert any sulphite to sulphate and the latter is precipitated and weighed as barium sulphate, in which form the sulphur is accurately weighed.

DISTILLATION TEST

This method of test is not normally used for residue fuel oils but enters into the specification of kerosines and distillate diesel fuels. A measured volume of the oil (100 ml. for kerosines and 200 ml. for gas oil or similar distillate fuels) is distilled at the specified rate of 5 or 10 ml. per minute respectively. The volume of condensate is noted at each 10° C. (or alternatively the temperature recorded as each 10 per cent. of the sample has collected in the receiver). In the case of kerosine the final boiling point is noted, i.e. the maximum temperature recorded at the end of the distillation; in the case of gas oil the distillation is generally stopped at 360° C. because further heating causes cracking of the residue in the distillation flask. In either case the residue in the flask is measured when cool. The difference between liquid taken and liquid recovered plus residue represents distillation loss.

Distillation temperatures are, of course, affected by barometric pressure, but it is customary not to apply any correction except in cases of dispute, though the barometric pressure at the time of test should be recorded.

CARBON RESIDUE

Conradson Method

This test determines the amount of carbonaceous residue that remains when an oil is evaporated under the specified conditions. It is designed to give an indication of the coke-forming tendencies of the oil at high temperatures.

In the Conradson test, ten grams of the oil are weighed into a tared porcelain or silica crucible which forms the innermost component of the nest of crucibles shown in the figure. The second crucible, which has a lid with a small aperture, is of iron and stands on a layer of sand inside a third crucible of sheet iron, the whole being enclosed in a sheet metal casing. The whole system is heated by a gas burner at such a rate that oil vapours cease to be generated after 13 minutes. The temperature is then raised to full redness for a further 7 minutes and the crucible is allowed to cool and then weighed. The carbon residue is expressed as a percentage of the oil used. When the carbon residue is greater than 5 per cent. or less than 0.05 per cent. the test must be repeated with more suitable quantities of oil as specified in "Standard Methods".

Ramsbottom Method

In this method, which is now generally preferred to the Conradson method, the nest of crucibles is replaced by a tared glass bulb with a small capillary which permits egress of the oil vapours. The bulb is heated in a bath of molten metal maintained at 550° C. The quantity of oil used may be 4 g., 2 g. or 1 g., according to the magnitude of the carbon residue. The procedure is then similar to the former test, the weight of bulb and carbon being determined at the end of the test and the carbon residue expressed as a percentage.

The values given by the two tests are not identical or even comparable.

WATER CONTENT

Though fuel oils do not normally contain more than a fractional percentage of water, wet oils are occasionally met with. Consequently the standard procedure for determining the water content is described here. The method is sometimes known as the Dean and Stark test.

A measured volume of the oil, which may be 100 ml. or other suitable quantity, is placed in a round flask, together with an equal volume of a "carrier liquid" consisting of a petroleum spirit boiling between 90° C. and 160° C. and containing not more than 20 per cent. boiling below 100° C.

The mixture is boiled and the vapours of water and of the carrier liquid are condensed in the reflux condenser. The water collects in the graduated receiver below a layer of carrier liquid, the excess of which flows back into the flask; ultimately the whole of the water is thus transferred to the receiver where its volume is measured. There is a variety of standardised receivers of different capacities suitable for dealing with various degrees of wetness of the oils concerned.

ANILINE POINT

This is the temperature in degrees Fahrenheit at which the oil just becomes completely miscible with an equal volume of aniline.

It is a convenient laboratory test for assessing the proportion of aromatic hydrocarbons in hydrocarbon mixtures such as petroleum fuels, because aromatic hydrocarbons have a much lower Aniline Point than paraffin or naphthene hydrocarbons of the same boiling range. Consequently a low Aniline Point (and, therefore, a low Diesel Index, which is based on aniline point) indicates a high aromatic content and, therefore, a low cetane number.

The Aniline Point is determined by mixing in a test tube, provided with a stirrer and thermometer, equal volumes of the oil (which must be dry) and pure dry freshly distilled aniline. The mixture is slowly warmed with constant stirring until complete miscibility is just attained and then allowed to cool slowly until separation just occurs. The miscibility temperature, or aniline point, can be determined accurately within 0.2°F. , provided the aniline is pure and no moisture is present.

DIESEL INDEX

This characteristic of a diesel fuel oil assesses its ignition qualities indirectly where these cannot be determined by the preferable direct measurement of the Cetane Number in a standardised engine test. The diesel index is calculated from the formula :

$$\text{Diesel Index} = \frac{\text{Aniline Point} \times \text{A.P.I. Gravity}}{100}$$

SPECIFIC GRAVITY

The A.P.I. This is derived from the Specific Gravity at 60°F. by reference to tables or from the formula:

$$\text{A.P.I. Gravity} = \frac{141.5}{\text{Sp. Gr. at } 60^{\circ}\text{F.}} - 131.5$$

ANALYSIS OF GASES

Although the analysis of fuels and other materials of importance in fuel technology is generally left to a qualified analyst, that of flue gases may quite reasonably be undertaken by those not necessarily so qualified but concerned with boiler efficiency tests and similar testing procedure. Consequently the apparatus generally used for that purpose is described below.

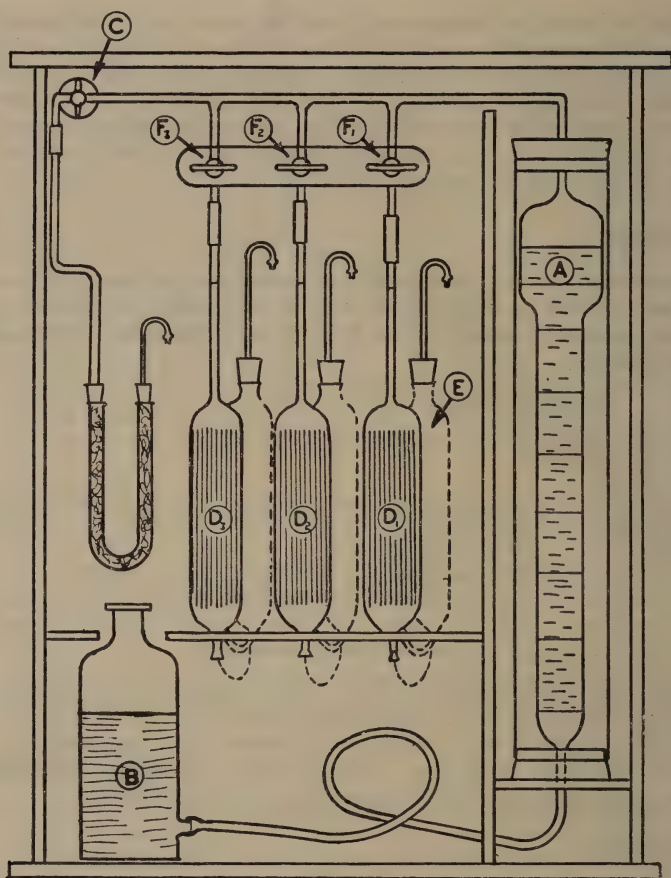
GASEOUS FUELS

Much light can be thrown on the efficiency of operation of gas producers and blast furnaces as well as of some metallurgical plant, by analysis of the gases evolved. For very accurate work detailed analysis, involving determination of many constituents, is necessary. For that type of work elaborate apparatus such as that of Bone & Wheeler is used and in some cases difficult mathematical calculations are involved, especially where several hydrocarbon gases are present.

The Orsat apparatus described below, designed to ascertain the proportions of the main constituents of flue gases, gives information that is frequently of value in this field.

FLUE GASES

Many gases may be present in a flue gas. The combustion engineer is normally concerned with the percentage composition in respect of (i) carbon dioxide, (ii) oxygen and (iii) carbon monoxide. The information conveyed by the simple analysis of this type throws sufficient light on the efficiency of combustion and on the amount of excess air that may have leaked into the flue system. Instruments that give this information automatically are described in Chapter 27. The combustion engineer requiring to check their accuracy, or faced with the problem of analysing flue gases for any other purpose, normally uses the Orsat apparatus or any other similar apparatus of which many kinds are available.



- A Graduated burette.
 B Aspirator bottle.
 C Stopcock for taking in gas sample.
 D_1, D_2, D_3 Absorbent liquids.
 E Displacement reservoirs.
 F_1, F_2, F_3 Stopcocks for burettes.

FIG. 1. Orsat gas analysis apparatus.

The Orsat apparatus, illustrated in Fig. 1, consists of a burette (A) graduated from the bottom upwards into 100 divisions, an aspirator bottle (B) and, in the simpler form of apparatus, three pipettes (D_1, D_2, D_3) each containing an absorbent for removing one gas. The first pipette contains a solution of caustic potash; this absorbs CO_2 (and SO_2 which may also be present). The second pipette contains a freshly prepared solution of alkaline pyrogallol (pyrogallic acid); this solution absorbs oxygen. The third pipette contains a solution of cuprous chloride in ammonia; this solution absorbs carbon monoxide (as well as acetylene and ethylene). Alternatively the solution of cuprous chloride may be one in hydrochloric acid.

The pipettes are generally filled with glass tubes or beads which provide a large surface to be moistened with the particular absorbent contained in the pipette. The Stanier pipette achieves the same object by forming innumerable

small bubbles of the gas throughout the absorbent liquid. Each pipette is connected by a U-limb to another pipette in which the bulk of the absorbed liquid is displaced when the gas is drawn into the main pipette.

The burette is surrounded by a wide water jacket so as to keep the temperature of the gas uniform throughout the test.

PROCEDURE FOR ANALYSIS

The aspirator bottle is first raised so as to fill the burette completely with water. The 3-way stopcock (C) connecting the top of the burette to the gas stream is then turned so as to allow the gas to be drawn into the burette, through a smoke filter, by lowering the aspirator bottle. This operation is repeated two or three times to purge the system, each successive lot of gas being expelled to the atmosphere by turning the stopcock into the appropriate position.

When it is judged that the system now contains only the flue gas, the water level in the burette is adjusted exactly to the zero mark (at the foot), the level of the water in the aspirator bottle being brought down level with the zero mark on the burette for this purpose. During this operation the observer must bring his eyes down to the same level, to avoid error of parallax. The burette now contains exactly 100 units of volume of the gas.

The measured sample of the gas is passed into the first pipette by opening the stopcock (F_1) and raising the aspirator bottle until the liquid in the burette rises just to the top. The liquid must not pass over into the stopcock manifold. By lowering the bottle again the gas is brought back into the burette. This operation is repeated two or three times until there is no further change in the level of the water in the burette. The new level is now noted, the difference being the percentage (by volume) of CO_2 present. The operation is repeated using the second pipette, but in this case it may be necessary to repeat the transferring operation 10 or 12 times. The additional change in volume represents the percentage of O_2 . The operation is repeated using the third pipette (containing the cuprous chloride). The difference represents the percentage of CO present. As the absorption of CO is a reversible reaction, complete absorption may not be achieved, especially if the percentage of CO is relatively large. For that reason it is common practice to have a fourth pipette also containing cuprous chloride solution, into which the gas is passed after using the third. If this practice is followed, the liquid in the third pipette is in due course thrown away and the fourth pipette is moved up into the third position (or if more convenient the liquid in it is transferred into the empty third pipette). The empty pipette, occupying the fourth position, is now filled with fresh solution.

After each absorption, of course, the aspirator bottle must be held alongside the burette in such a position that the level of the water in the bottle is the same as the new level of the water in the burette, not that of the zero mark.

The solutions must be used in the order stated above. This is because the liquid in the second pipette, being strongly alkaline, can absorb carbon dioxide as well as oxygen, and that in the third pipette, containing cuprous chloride, can absorb oxygen as well as carbon monoxide.

It will be noted that the procedure gives the composition of the gas as measured over water. Since CO_2 is soluble in water, precautions have to be taken to guard against error due to loss by absorption. Various expedients are adopted. For example water acidulated with sulphuric acid may be used in the burette and aspirator bottle, this both lessening the solubility of CO_2 and incidentally absorbing any trace of ammonia vapour derived from the third pipette. The water may be lightly coloured, preferably with a few drops

of methyl orange indicator, so as to make it more easily visible through the surrounding water in the water jacket. If an indicator is used there is the additional advantage that accidental contamination by alkali from one of the pipettes would be automatically detected.

Any sulphur dioxide present will be recorded as if it were CO_2 : a correction may have to be applied. For this purpose a separate analysis may be made, or an adjustment based upon the known sulphur content of the fuel can be applied. In general, no harm results if the correction is not applied, so far as concerns excess air calculations, but if the analysis is being performed as a check on the accuracy of a CO_2 indicator or recorder the principle of operation of the instrument will have to be ascertained before deciding on the proper course of action.

It will be seen that care must be exercised in applying the results of a gas analysis made by the Orsat or other simple apparatus, whatever the object of making the test.

Detailed instructions⁶ for the sampling and analysis of flue gases are given in B.S. 1756.

MAINTENANCE OF ORSAT APPARATUS

The Orsat apparatus is an invaluable aid to the intelligent operation of boiler and furnace plant, but it must be kept clean and in perfect order. The stop cocks must be frequently removed, washed, dried and then very lightly greased. The parts of the tubes into which they fit must be similarly treated. Care must be taken to avoid using so much grease that the small-bore tubes become blocked. Another important precaution relates to bringing the absorbent liquids to their respective levelling marks immediately above the pipettes; the liquids must not be allowed to rise above these marks into the stopcocks. The absorbing solutions readily leave deposits that in the course of time cause the stopcocks to "seize".

GENERAL NOTE

The treatment of the subject of analysis of fuels in this chapter is not intended to replace the detailed instructions prescribed elsewhere for the procedure to be followed. Any person having to make any of the determinations referred to must obtain the appropriate British, or Institute of Petroleum, Standard.

REFERENCES

- ¹ B.S. 1016. *Methods for the Analysis and Testing of Coal and Coke*. London. British Standards Institution. Pt. 1. Total Moisture of Coal. Pt. 2 Total Moisture of Coke. Pt. 3. Proximate Analysis of Coal. Pt. 4. Proximate Analysis of Coke. Pt. 5. Calorific Value of Coal and Coke. Pt. 6. Ultimate Analysis of Coal. Pt. 7. Ultimate Analysis of Coke. Pt. 8. Chlorine. Pt. 9. Phosphorus. Pt. 10. Arsenic. Pt. 11. Forms of Sulphur in Coal. Pt. 12. Caking Properties of Coal. Pt. 13. Tests special to Coke. Pt. 14. Analysis of Ash. Pt. 15. Ash Fusibility. Pt. 16. Reporting of Results.
- ² *Methods of Analysis of Coal and Coke*. 1940. Fuel Research Survey Paper No. 44. London. H.M.S.O.
- ³ *Improved Methods for the Quantitative Analysis of Coal and Coke Ash*. 1949. Fuel Research Survey Paper No. 50. London. H.M.S.O.
- ⁴ *Report of the Coal Grading Committee on the Size Grading of British Coals*. 1946. London. British Colliery Owners' Research Association.
- ⁵ *Standard Methods for Testing Petroleum and its Products*. 15th Edition. 1956. London. The Institute of Petroleum.
- ⁶ *Code for the Sampling and Analysis of Flue Gases*. B.S. 1756. London. The British Standards Institution.

UNITS AND CONVERSION FACTORS AND OTHER USEFUL INFORMATION

LENGTH

1 Ångstrom Unit (A.U., Å) = 1/10-million millimetre = 1×10^{-8} centimetre
 $= 3.937 \times 10^{-9}$ inch.
1 micron (μ) = 1/million metre = 1×10^{-4} centimetre = 3.937×10^{-5} inch.
1 inch (in.) = 2.5400 centimetres (cm.). 1 cm. = 0.3937 in.
1 foot (ft.) = 12 in. = 30.480 cm.
1 yard (yd.) = 0.9144 metre. 1 metre (m.) = 1.094 yd. = 39.370113 in.
1 statute mile [U.K.] = 1,760 yd. = 1.6093 kilometres (km.).
1 km. = 0.6214 mile.
1 metre (m.) = 3.2808 ft. = 1.0936 yd.

VOLUME

1 litre (l.) = 1.7598 pints = 0.219975 gallon. 1 millilitre (ml.) = 0.001 l.
= 1.000028 cubic centimetre (c.c.).

1 pint [U.K.] = 0.5682 l.

1 Imperial gallon [U.K.] (gal.) of water occupies 0.1604 cu. ft. = 8 pints,
= 4.5459631 l. = 1.201 (1.20094). U.S. gal. = 10 lb. of water
(at 60° F.).

1 U.S. gal. = 0.8327 Imperial gal. = 6.661 pts. = 0.1336 cu. ft.

1 cubic foot (cu. ft.) of water at 60° F. = $6\frac{1}{4}$ (6.24) Imperial gal. = $62\frac{1}{2}$ lb.

1 barrel [U.S. liquid] = 31.5 gal.

1 cubic inch (cu. in.) = 6.9444×10^{-3} cu. ft. = 6.4516 c.c.

1 c.c. = 0.061024 cu. in.

1 cu. ft. = 0.028317 cu. m. 1 cu. m. = 35.3148 cu. ft.

WEIGHT

1 ounce [avoirdupois] (oz.) = 28.3495 grammes.
 1 pound [avoir.] (lb.) = 16 oz. = 14.583 oz. troy = 453.6 (453.5923) gm.
 1 (long) ton (U.K.) = 2,240 lb. = 1.12 short ton
 = 1.016 metric tons [tonnes].
 1 short ton (U.S.) = 2,000 lb. = 0.8929 long ton = 0.9072 tonne.
 1 gramme (gm. or g.) = 15.432 grains = 0.035274 oz. (avoir.).
 1 grain (gr.) = 0.0648 gm. = 2.2857×10^{-3} oz. = 1.4286×10^{-4} lb.
 1 lb. = 7,000 gr. 1 gal. = 70,000 gr. (approx.)

DENSITY AND CONCENTRATION

1 gm./ml. = 0.999972 gm./c.c. = 62.4259 lb./cu. ft. = 10.0221 lb./gal.
 = 43,698,130 gr./100 cu. ft. = 70,155 gr./gal.
 1 kg./cu. m. = 1 oz./cu. ft. (accurately to 1/7 of 1 per cent.)
 1 lb./cu. ft. = 16.019 kg./cu. m.

TEMPERATURE

In these tables and generally throughout this book the symbol ° is used to designate an exact position on a thermometer or other temperature scale, e.g. 212° F., 100° C. The expression "deg." is used to indicate a range in temperature, e.g. a rise in temperature from (say) 150°C. to 200° C. is 50 deg. C. (not 50° C.).

1 Fahrenheit degree (deg. F.) = $\frac{5}{9}$ of one Centigrade degree (deg. C.).

1 deg. C. = $\frac{9}{5}$ of 1 deg. F.

$$(^{\circ}\text{F.} - 32) \times \frac{5}{9} = ^{\circ}\text{C.} \quad \text{or} \quad (^{\circ}\text{C.} \times \frac{9}{5}) + 32 = ^{\circ}\text{F.}$$

The following is a convenient alternative formula for inter-conversion of Fahrenheit and Centigrade temperature readings:

Irrespective of direction of conversion, add 40 to the actual temperature, multiply by 9/5 (C→F) or 5/9 (F→C), then deduct 40. Note: $-40^{\circ}\text{C.} = -40^{\circ}\text{F.}$

Absolute temperature scales

$$^{\circ}\text{C.} + 273 = ^{\circ}\text{Absolute} = ^{\circ}\text{K.}$$

$$^{\circ}\text{F.} + 460 = ^{\circ}\text{F. Absolute} = ^{\circ}\text{Rankine}$$

Some important or interesting temperatures

Electric arc furnace	.. ..	3,600° C. (approx.)
Tungsten, m.p.	.. ..	3,000° C. (approx.)
Silica, quartz, m.p.	.. ..	1,710–1,750° C.
Iron (pure), m.p.	.. ..	1,535° C.
Iron (pig or cast), m.p.	.. ..	1,100° C. (approx.)
Copper, m.p.	.. ..	1,083° C.
Gold, m.p.	.. ..	1,063° C.
Aluminium, m.p.	.. ..	648° C.
Mercury, b.p.	.. ..	356.9° C.
Lead, m.p.	.. ..	327.4° C.
Solder (lead-tin eutectic)	.. ..	183° C.
Water, b.p. (at atmospheric pressure)	.. ..	100° C.
Ice, m.p. (at atmospheric pressure)	.. ..	0° C.
Mercury, m.p.	.. ..	–38.9° C.
Liquid air, b.p.	.. ..	–187° C.
Absolute zero	.. ..	–273.16° C.
White heat	.. .. above about	1,700° C.
Cherry-red heat	.. .. mid-point	800° C.
Dark red heat	.. .. mid-point	625° C.
Red heat, barely visible	.. ..	525° C.

These figures are all very approximate as they depend upon surrounding illumination

PRESSURE

1 atmosphere (atm.) at 0° C. = 14.695 lb./sq. in. = 760 mm. mercury (Hg)
= 29.92 in. Hg = 33.90 ft. of water = 1.0332 kg./sq. cm.

= 1,013.2 millibars = 2,116.0 lb./sq. ft.

1 inch water (4°C.) = 1.869 mm. Hg = 0.07358 in. Hg

= 0.03613 lb./sq. in.

1 lb./sq. in. = 0.070307 kg./sq. cm.

HEAT, ENERGY, POWER

The basic unit of heat is the Joule = 1 Watt-sec. = 10,000,000 ergs.

The unit of heat in any system is the amount of heat required to raise the temperature of unit mass of water through one degree on the temperature scale applicable. Its absolute value in all systems is slightly greater at lower temperatures than at higher temperatures.

HEAT UNITS

Amount of water heated	Range through which heated	Name of unit	Abbreviation
1 lb.	one deg. F.	British Thermal Unit	B.t.u.
1 gm.	one deg. C.	calorie	cal.
1 kg.	one deg. C.	kilogramme-calorie	kcal.
1 lb.	one deg. C.	Centigrade Heat Unit	C.H.U.

International Steam Table calorie = 4.1868 Joules.
Mean calorie, 0°-100° C. = 4.1897 Joules.
Mean B.t.u. 60°-61° F. = 1,054.54 Joules.
Mean B.t.u. 32°-212° F. = 1,055.79 Joules.
1 therm = 100,000 B.t.u. = 25,200 kcal. = 29.30 kWh = 39.28 hph.
1 B.t.u. = 252 cal. = 778 ft. lb. = 2.930×10^{-4} kWh
1 kcal. = 3.968 B.t.u.
1 C.H.U. = 1.8 B.t.u. = 453 cal.
1 megawatt (MW) = 1 million Watts.
1 kilowatt hour (kWh) = 1,000 Watt-hours = 1.34 hph = 3,600,000 Joules.
1 horsepower-hour (hph) = 0.746 kWh.

CALORIFIC VALUE

Calorific values of fuel are expressed variously, e.g. as follows:

- (a) calories per gramme (cal./gm.)
- (b) kilogramme calories per kilogramme (kcal./kg., Cal./kg.)
- (c) British thermal units per pound (B.t.u./lb.)
- (d) B.t.u. per gallon (B.t.u./gal.)
- (e) B.t.u. per cubic foot (B.t.u./cu. ft.)
- (f) C.H.U. per pound (C.H.U./lb.)
- (g) kilogramme calories per cubic metre.

Any value for (a) will, by definition, be identical with values for (b) and (f)
 $\text{B.t.u./lb.} \times 0.5556 = \text{cal./gm.}$ $\text{cal./gm.} \times 1.8 = \text{B.t.u./lb.}$

For gaseous fuels:

B.t.u./cu. ft. at 30 in., 60° F. sat. $\times 9.547 = \text{kcal./cu. m. at N.T.P. dry,}$
 $9.487 = \text{kcal./cu. m. at N.T.P. sat.}$

kcal./cu.m. at N.T.P., dry, $\times 0.1047 = \text{B.t.u./cu. ft. at 60° F., 30 in.}$
Hg sat.

kcal./cu. m. at N.T.P., sat, $\times 0.1054 = \text{B.t.u./cu. ft. at 60° F. 30 in.}$
Hg sat.

kcal./cu. m. at 15°C., 760 mm. dry, $\times 0.1105 = \text{B.t.u./cu. ft. at 60° F., 30 in.}$
Hg sat.

kcal./cu. m. at 15° C., 760 mm. sat, $\times 0.1124 = \text{B.t.u./cu. ft. at 60° F., 30 in.}$
Hg sat.

(N.T.P. :—760 mm. Hg, 0°C.)

LIQUID FUEL CONVERSIONS AND SPECIFIC GRAVITIES

UNITED KINGDOM			OVERSEAS	
	<i>Average specific gravity</i>	<i>Imperial gallons per long ton</i>	<i>Barrels per long ton</i>	<i>Barrels per long ton</i>
Crude and process oils. .	0.862	260	7.4	7.3
Aviation spirit . .	0.712	315	9.0	9.0
Motor do. . .	0.725	309	8.8	8.8
Industrial do. . .	0.716	313	8.9	} 8.1
White do. . .	0.778	288	8.2	
Kerosine . .	0.806	278	7.9	8.0
Burning oil . .	0.789	284	8.1	8.1
Vaporising oil . .	0.824	272	7.8	7.7
Gas/diesel oil . .	0.842	266	7.6	7.4
Fuel oil. .	0.954	235	6.7	6.7
Lubricating oils . .	0.915	245	7.0	6.9
Butane . .	0.582	385	11.0	11.0
Propane . .	0.504	445	12.7	12.7

These liquid fuel conversion factors are those used in the Ministry of Fuel and Power Statistical Digest for the year 1955. They may apply only approximately in respect of certain items relating to fuel statistics of former years.

"COAL EQUIVALENTS"

It is unwise to attempt to give reliable figures purporting to relate coal on a purely thermal basis to any other fuel; there can be no absolute standard for comparison. A so-called *standard coal* has been defined as one of calorific value 12,500 B.t.u./lb. but such a standard has not received official recognition. Eight lb. of this standard coal = 29.3 kWh., or one therm. Thermally, one ton of coal is very approximately equal to one ton of coke.

Calorific values. The calorific values of fuels vary according to the quality, especially (in the case of solid fuels) according to ash content. Consequently the following (gross) calorific values and equivalent values may be regarded as typical examples only and should be used with all caution in any calculations based on them.

The net C.V. of a coal is lower than the gross C.V. by an amount varying from under 1 per cent. of the gross C.V. in the case of an anthracite, to 3-4 per cent. in the case of a bituminous coal and over 6 per cent. in the case of a high-volatile coal. The difference in the case of most fuel oils is about 6 per cent

Fuel	Gross Calorific Value			Equivalent of 1 therm	
	cal./gm.	B.t.u./lb.	therms/ton	lb.	
Anthracite	8,054	14,500	325	6.90	
Gas coal	7,443	13,400	300	7.46	
House coal	6,943	12,500	280	8.00	
Domestic gas coke	6,943	12,500	280	8.00	
Coal for electricity generating stations	5,972	10,750	241	8.22	
			therms/gal.	gal.	
Kerosine (paraffin oil)	11,110	20,000	1.60	0.65	
Gas oil	10,888	19,600	1.66	0.60	
Diesel oil fuel	10,888	19,600	1.66	0.60	
Heavy oil fuel	10,416	18,750	1.85	0.54	
Coal tar fuel C.T.F. 200	9,166	16,500	1.85	0.54	
	kcal./cu. m.†	B.t.u./cu. ft.*		cu. m.	cu. ft.
Town gas, no steaming C.V.R.	4,804	540		5.24	185
" " steaming C.V.R. ..	4,226	475		4.62	163
" " as delivered ..	4,226-4,448	475-500		—	210-200
Producer gas, hand operated, coke	1,112	125		22.31	800
" " from coal, mechanically operated ..	1,468	165		19.5	650
" " from coke	1,157	130		21.8	770
Blast furnace gas, CO ₂ : 11%, CO: 27%, H ₂ : 2%, N ₂ : 60%	819	92		30.6	1,080
Coke oven gas, debenzolized ..	4,671	525		5.37	190
Hydrogen	2,847	320		8.9	313
Carbon monoxide	2,829	318		8.94	315
Methane	8,852	995		2.97	105
Benzene (C ₆ H ₆)	33,274	3,740		0.755	26.6
Sulphuretted hydrogen	5,605	630		4.5	159

† At 760 mm. Hg, 15°C., saturated.

* At 30 in. Hg, 60° F., saturated.

GREEK ALPHABET

For the convenience of readers not familiar with the Greek letters commonly used in formulae and other expressions, the classical Greek alphabet is given below.

A	α	alpha	I	ι	iota	P	ρ	rho
B	β	beta	K	κ	kappa	Σ	σ s	sigma
Γ	γ	gamma	Λ	λ	lambda	T	τ	tau
Δ	δ	delta	M	μ	mu	Υ	υ	upsilon
E	ϵ	epsilon	N	ν	nu	Φ	ϕ	phi
Z	ζ	zeta	Ξ	ξ	xi	X	χ	chi
H	η	eta	O	\omicron	omicron	Ψ	ψ	psi
Θ	θ	theta	Π	π	pi	Ω	ω	omega

APPENDIX B

STATISTICS OF FUEL AND ENERGY RESOURCES AND CONSUMPTION

TABLE I
WORLD RESOURCES OF FOSSIL FUELS^{*(a)}

<i>Resource</i>	<i>Bituminous Coal Equivalent</i>	
	<i>Thousand million tons</i>	<i>Per cent. of total</i>
Coals and lignites	4,400	91.8
Petroleum	150	3.1
Natural gas with petroleum ..	90	1.9
Methane in coal measures ..	45	0.9
Oil in oil shale	45	0.9
Peat	65	1.4
Total	4,795	100.0

*As indicated in Chapter 1, estimates of mineral resources vary widely, not only because of different criteria applied by different workers but also because of different methods of assessment as between different countries. Figures for resources of coal, for example, may allow for total "workable seams" (above an agreed "reasonable" thickness) or, on the other hand, for 75 per cent., or even only 50 per cent., of the coal being extractable and raised to the surface. Probably not more than one-third to one-half of the reserves of coal and lignites could be economically mined.

TABLE 2
WORLD CONSUMPTION OF FUEL AND ENERGY IN 1954
EXPRESSED IN BITUMINOUS COAL EQUIVALENTS^(a)

<i>Fuel or energy</i>	<i>Coal equivalent : million tons</i>	<i>Per cent. of total</i>
Coals and lignites	1,650	45.2
Petroleum	1,050	28.8
Natural gas	400	11.0
Wood	250	6.8
Water power	230	6.3
Peat, shale oil, waste materials, etc. ..	70	1.9
Total	3,650	100.0

^(a)Based, by permission of the author, Dr. A. Parker, C.B.E., D.Sc., F.R.I.C., F.Inst.F., on the 1955 Melchett (Institute of Fuel) Lecture and the 1956 Mitchell Memorial (Stoke-on-Trent Assocn. of Engrs.) Lecture.

TABLE 3
PRODUCTION AND CONSUMPTION OF PRIMARY FUELS
IN THE UNITED KINGDOM

Million statute tons of coal equivalent.⁽¹⁾

	Production				Inland Consumption		
	Total	Coal	Oil	Hydro-electricity	Total ⁽²⁾	Coal ⁽³⁾	Oil
1913 ..	287.8	287.4	0.4	—	190.9	188.9	2.0
1929 ..	258.4	257.9	0.3	0.2	184.6	177.2	7.2
1937 ..	241.2	240.4	0.2	0.6	198.1	185.8	11.7
1948 ..	210.3	209.2	0.2	0.9	212.1	191.9	19.3
1950 ..	217.2	216.1	0.2	0.9	224.6	201.0	22.7
1951 ..	224.3	223.1	0.2	1.0	232.5	206.5	25.0
1952 ..	227.8	226.6	0.2	1.0	231.9	204.8	26.1
1953 ..	225.4	224.2	0.2	1.0	235.7	206.4	28.3
1954 ..	225.8	224.3	0.2	1.3	245.8	213.1	31.4
1955 ..	223.2	222.1	0.2	0.9	249.6	213.8	34.9

⁽¹⁾ The coal equivalent of oil (only those products used as fuel being included here) is assumed to be 1.7 times its weight, and the coal equivalent of hydro-electricity is the quantity of coal that would be required to produce it in thermal power stations.

⁽²⁾ Including hydro-electricity not shown separately, as its consumption is the same as its production.

⁽³⁾ After deducting the quantity of secondary solid fuels added to stocks or exported.

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APPENDIX C.

AREAS OF BRITISH COALFIELDS AND RESPECTIVE PRODUCTION FIGURES

Coalfield	Approximate Area (sq. miles)	1954 Output* (thousand tons)	Per Cent. of each Coal Type in Output										
			100	201	202, 203, 204	301	400	500	600	700	800	900	206, 305, 306
Fife ..	175	6,261	—	—	—	2	—	—	2	1	34	57	4
Clackmannan ..	40	630	—	—	—	—	—	—	—	—	18	77	5
Lothians ..	125	3,878	—	—	—	—	—	—	—	4	73	23	—
Central ..	600	7,340	3	—	—	4	—	8	20	26	24	4	11
Ayrshire ..	375	3,368	—	—	—	—	—	—	12	41	33	3	—
Dumfriesshire (Sanquhar)	20	536	—	—	—	—	—	—	34	66	—	—	—
Douglas ..	30	866	—	—	—	—	—	—	1	41	57	1	—
Campbeltown ..	10	109	—	—	—	—	—	—	—	—	—	100	—
Northumberland ..	275†	14,248	—	—	—	1	4	22	16	41	16	0	—
Cumberland ..	150	1,443	—	—	—	—	—	100	—	—	—	—	—
Durham ..	575†	29,326	0	—	—	26	25	41	4	1	—	—	3
Yorkshire ..	1,450	50,098	—	—	—	0	4	34	25	24	12	1	—
Lancashire ..	650	15,462	—	—	—	1	3	18	34	23	20	1	—
North Wales ..	225	2,474	—	—	—	—	—	33	49	18	—	—	—
Nottinghamshire and North Derbyshire ..	750	40,251	—	—	—	—	1	5	17	22	36	19	—
South Derbyshire ..	35	3,571	—	—	—	—	—	—	—	6	45	49	—
Leicestershire ..	35	4,638	—	—	—	—	—	—	—	—	100	—	—
North Staffordshire ..	200	6,115	—	—	—	—	4	22	24	35	15	0	—
Cannock Chase ..	75	5,374	—	—	—	—	—	—	—	1	93	6	—
South Staffordshire ..	125	783	—	—	—	—	—	—	—	2	86	12	—
Shropshire ..	250	654	—	—	—	—	—	—	—	52	48	—	—
Warwickshire ..	150	5,337	—	—	—	—	—	—	—	—	67	33	—
South Wales ..	900	29,657	12	18	31	33	1	2	1	0	—	—	1
Forest of Dean ..	35	612	—	—	—	—	—	—	39	61	—	—	—
Bristol and Somerset ..	275	674	—	—	—	28	71	—	—	—	—	—	—
Kent ..	200	2,018	—	—	35	65	—	—	—	—	—	—	1
TOTAL	7,730	235,723	1.7	2.3	4.2	8.4	4.9	17.8	14.1	16.4	19.7	9.4	1.1

* Raised and weighed output, excluding non-N.C.B. mines and opencast coal.

† Coal Measures area only

0 signifies less than $\frac{1}{4}$ per cent.;—signifies nil.

APPENDIX D

STEAM TABLES*

TABLE I. THE PROPERTIES OF SATURATED STEAM AND WATER

In. Hg. vacuum	Abs. press: lb./sq.in.	Temper- ature °F.	HEAT: B.t.u./lb.			VOLUME: cu.ft./lb.		ENTROPY: B.t.u./deg.F.Abs./lb.		
			Sensible	Latent	Total	Liquid	Vapour	Liquid	Evap.	Total
29.5	.245	58.8	26.8	1060.5	1087.3	.0160	1257	.053	2.045	2.098
29.25	.376	70.2	38.3	1053.8	1092.1	.0161	860	.075	1.989	2.064
29	.490	78.9	47.0	1049.1	1096.1	.0161	656	.091	1.948	2.039
28.75	.612	85.8	53.8	1045.2	1099.0	.0161	532	.104	1.916	2.020
28.5	.735	91.6	59.6	1041.9	1101.5	.0161	447	.114	1.890	2.004
28.25	.857	96.6	64.6	1039.3	1103.9	.0161	387	.123	1.868	1.991
28	.979	101.0	69.0	1036.7	1105.7	.0161	341	.131	1.849	1.980
27.75	1.102	105.0	72.9	1034.6	1107.5	.0162	305	.138	1.832	1.970
27.5	1.224	108.6	76.6	1032.4	1109.0	.0162	276	.145	1.816	1.961
27.25	1.347	111.8	79.9	1030.6	1110.5	.0162	252	.150	1.803	1.953
27	1.469	114.9	82.9	1028.9	1111.8	.0162	233	.156	1.790	1.946
26.5	1.714	120.5	88.4	1025.7	1114.1	.0162	201	.165	1.768	1.933
26	1.958	125.3	93.2	1022.8	1116.0	.0162	177	.174	1.748	1.922
25.5	2.203	129.7	97.6	1020.3	1117.9	.0163	159	.181	1.732	1.913
25	2.448	133.6	101.5	1018.1	1119.6	.0163	144	.188	1.716	1.904
24.5	2.693	137.3	105.2	1015.9	1121.1	.0163	132	.194	1.702	1.896
24	2.938	140.7	108.7	1013.9	1122.6	.0163	121	.200	1.689	1.889
23.5	3.183	143.8	111.8	1012.1	1123.9	.0163	112	.205	1.677	1.882
23	3.428	146.8	114.7	1010.3	1125.0	.0163	105	.210	1.666	1.876
22.5	3.672	149.5	117.4	1008.8	1126.2	.0163	98.4	.214	1.657	1.871
22	3.917	152.1	120.0	1007.2	1127.2	.0164	92.6	.218	1.647	1.865
21.5	4.162	154.6	122.5	1005.8	1128.3	.0164	87.5	.222	1.638	1.860
21	4.407	157.0	124.9	1004.2	1129.1	.0164	82.9	.226	1.629	1.855
20	4.896	161.4	129.3	1001.7	1131.0	.0164	75.1	.233	1.614	1.847
19	5.386	165.4	133.3	999.4	1132.7	.0164	68.7	.240	1.599	1.839
18	5.876	169.2	137.1	997.1	1134.2	.0164	63.3	.246	1.586	1.832
17	6.365	172.7	140.6	995.0	1135.6	.0165	58.8	.252	1.573	1.825
16	6.855	175.9	143.8	993.1	1136.9	.0165	54.8	.257	1.562	1.819
15	7.344	178.9	146.8	991.3	1138.1	.0165	51.4	.261	1.552	1.813
14	7.834	181.9	149.8	989.4	1139.2	.0165	48.4	.266	1.542	1.808
13	8.324	184.7	152.7	987.7	1140.4	.0165	45.7	.270	1.533	1.803
12	8.813	187.3	155.3	986.1	1141.4	.0166	43.3	.274	1.524	1.798
11	9.303	189.8	157.8	984.7	1142.5	.0166	41.2	.278	1.516	1.794
10	9.793	192.2	160.2	983.2	1143.4	.0166	39.2	.282	1.508	1.790
9	10.28	194.5	162.5	981.8	1144.3	.0166	37.5	.286	1.500	1.786
8	10.77	196.8	164.8	980.4	1145.2	.0166	35.9	.289	1.493	1.782
7	11.26	198.9	167.0	979.1	1146.1	.0166	34.4	.292	1.487	1.779
6	11.75	201.0	169.1	977.7	1146.8	.0166	33.1	.295	1.480	1.775
5	12.24	203.0	171.0	976.5	1147.5	.0167	31.9	.298	1.474	1.772
4	12.73	204.9	172.9	975.3	1148.2	.0167	30.7	.301	1.468	1.769
3	13.22	206.8	174.8	974.0	1148.8	.0167	29.7	.304	1.462	1.766
2	13.71	208.6	176.6	972.9	1149.5	.0167	28.7	.307	1.456	1.763
1	14.20	210.3	178.4	971.7	1150.1	.0167	27.7	.310	1.450	1.760

*These tables are based on the values given in the 1939 Callendar Steam Tables, by permission of Messrs. Edward Arnold and Co.

TABLE I. THE PROPERTIES OF SATURATED STEAM AND
WATER—*continued*

PRESSURE: <i>lb./sq.in.</i>		Temper- ature °F.	HEAT: <i>B.t.u./lb.</i>			VOLUME: <i>cu.ft./lb.</i>		ENTROPY: <i>B.t.u./deg.F.Abs./lb.</i>		
<i>gauge</i>	<i>Absolute</i>		<i>Sensible</i>	<i>Latent</i>	<i>Total</i>	<i>Liquid</i>	<i>Vapour</i>	<i>Liquid</i>	<i>Evap.</i>	<i>Total</i>
0	14.69	212	180.2	970.6	1150.8	0.0167	26.8	0.312	1.445	1.757
1	15.7	215.4	183.6	968.4	1152.0	0.0167	25.2	0.317	1.435	1.752
2	16.7	218.5	186.8	966.4	1153.2	0.0168	23.8	0.322	1.425	1.747
3	17.7	221.5	189.8	964.5	1154.3	0.0168	22.5	0.326	1.416	1.742
4	18.7	224.5	192.7	962.6	1155.3	0.0168	21.4	0.331	1.407	1.738
5	19.7	227.4	195.5	960.8	1156.3	0.0168	20.4	0.335	1.399	1.734
6	20.7	230.0	198.1	959.2	1157.3	0.0168	19.4	0.339	1.391	1.730
7	21.7	232.4	200.6	957.6	1158.2	0.0169	18.6	0.342	1.384	1.726
8	22.7	234.8	203.1	956.0	1159.1	0.0169	17.9	0.346	1.376	1.722
9	23.7	237.1	205.5	954.5	1160.0	0.0169	17.2	0.349	1.370	1.719
10	24.7	239.4	207.9	952.9	1160.8	0.0169	16.5	0.352	1.363	1.716
11	25.7	241.6	210.1	951.5	1161.6	0.0169	15.9	0.356	1.356	1.712
12	26.7	243.7	212.3	950.1	1162.3	0.0170	15.3	0.359	1.350	1.709
13	27.7	245.8	214.4	948.6	1163.0	0.0170	14.8	0.362	1.344	1.706
14	28.7	247.9	216.4	947.3	1163.7	0.0170	14.3	0.365	1.338	1.703
15	29.7	249.8	218.4	946.0	1164.4	0.0170	13.9	0.367	1.333	1.700
16	30.7	251.7	220.3	944.8	1165.1	0.0170	13.4	0.370	1.328	1.698
17	31.7	253.6	222.2	943.5	1165.7	0.0170	13.0	0.373	1.323	1.696
18	32.7	255.4	224.0	942.4	1166.4	0.0170	12.7	0.375	1.318	1.693
19	33.7	257.2	225.8	941.2	1167.0	0.0171	12.3	0.378	1.313	1.691
20	34.7	258.8	227.5	940.1	1167.6	0.0171	12.0	0.380	1.308	1.688
21	35.7	260.5	229.2	939.0	1168.2	0.0171	11.7	0.382	1.304	1.686
22	36.7	262.3	230.9	937.8	1168.7	0.0171	11.4	0.385	1.299	1.684
23	37.7	263.7	232.6	936.7	1169.3	0.0171	11.1	0.387	1.295	1.682
24	38.7	265.3	234.2	935.8	1169.8	0.0171	10.8	0.389	1.291	1.680
25	39.7	266.8	235.8	934.6	1170.4	0.0171	10.6	0.391	1.287	1.678
26	40.7	268.3	237.3	933.5	1170.8	0.0172	10.3	0.393	1.283	1.676
27	41.7	269.8	238.7	932.6	1171.3	0.0172	10.1	0.395	1.279	1.674
28	42.7	271.4	240.2	931.6	1171.8	0.0172	9.87	0.397	1.275	1.672
29	43.7	272.6	241.6	930.6	1172.2	0.0172	9.66	0.399	1.271	1.670
30	44.7	274.0	243.0	929.7	1172.7	0.0172	9.46	0.401	1.267	1.668
31	45.7	275.4	244.4	928.7	1173.1	0.0172	9.27	0.403	1.263	1.666
32	46.7	276.7	245.9	927.6	1173.5	0.0172	9.08	0.405	1.260	1.665
33	47.7	278.1	247.2	926.7	1173.9	0.0172	8.90	0.407	1.256	1.663
34	48.7	279.4	248.5	925.8	1174.3	0.0173	8.73	0.409	1.252	1.661
35	49.7	280.7	249.8	924.9	1174.7	0.0173	8.56	0.410	1.249	1.659
36	50.7	281.9	251.1	924.0	1175.1	0.0173	8.40	0.412	1.246	1.658
37	51.7	283.2	252.4	923.1	1175.5	0.0173	8.25	0.414	1.242	1.656
38	52.7	284.4	253.7	922.1	1175.8	0.0173	8.11	0.416	1.239	1.655
39	53.7	285.6	254.9	921.3	1176.2	0.0173	7.97	0.417	1.236	1.653
40	54.7	286.7	256.1	920.4	1176.5	0.0173	7.83	0.419	1.233	1.652
41	55.7	287.9	257.3	919.5	1176.8	0.0173	7.70	0.420	1.230	1.650
42	56.7	289.0	258.5	918.6	1177.1	0.0174	7.57	0.422	1.227	1.649
43	57.7	290.1	259.6	917.9	1177.5	0.0174	7.45	0.424	1.224	1.648
44	58.7	291.3	260.8	917.0	1177.8	0.0174	7.33	0.425	1.221	1.646
45	59.7	292.4	261.9	916.2	1178.1	0.0174	7.22	0.427	1.218	1.645

TABLE I. THE PROPERTIES OF SATURATED STEAM AND
WATER—continued

PRESSURE: <i>lb./sq.in.</i>		Temper- ature °F.	HEAT: <i>B.t.u./lb.</i>			VOLUME: <i>cu.ft./lb.</i>		ENTROPY: <i>B.t.u./deg.F. Abs./lb.</i>		
<i>gauge</i>	<i>Absolute</i>		<i>Sensible</i>	<i>Latent</i>	<i>Total</i>	<i>Liquid</i>	<i>Vapour</i>	<i>Liquid</i>	<i>Evap.</i>	<i>Total</i>
46	60.7	293.5	263.0	915.4	1178.4	.0174	7.10	.428	1.216	1.644
47	61.7	294.5	264.1	914.6	1178.7	.0174	6.99	.430	1.212	1.642
48	62.7	295.6	265.2	913.8	1179.0	.0174	6.89	.431	1.210	1.641
49	63.7	296.6	266.3	913.0	1179.3	.0174	6.78	.433	1.207	1.640
50	64.7	297.7	267.4	912.2	1179.6	.0174	6.68	.434	1.204	1.638
51	65.7	298.7	268.4	911.5	1179.9	.0174	6.59	.435	1.202	1.637
52	66.7	299.7	269.4	910.7	1180.1	.0175	6.50	.437	1.199	1.636
53	67.7	300.7	270.4	910.0	1180.4	.0175	6.41	.438	1.197	1.635
54	68.7	301.7	271.5	909.2	1180.7	.0175	6.32	.439	1.195	1.634
55	69.7	302.7	272.5	908.5	1181.0	.0175	6.24	.441	1.192	1.633
56	70.7	303.6	273.5	907.8	1181.3	.0175	6.16	.442	1.189	1.631
57	71.7	304.6	274.4	907.2	1181.6	.0175	6.08	.443	1.187	1.630
58	72.7	305.5	275.3	906.5	1181.8	.0175	6.00	.444	1.185	1.629
59	73.7	306.5	276.2	905.9	1182.1	.0175	5.92	.446	1.182	1.628
60	74.7	307.4	277.1	905.3	1182.4	.0175	5.84	.447	1.180	1.627
61	75.7	308.3	278.0	904.7	1182.7	.0176	5.77	.448	1.178	1.626
62	76.7	309.2	279.0	904.0	1183.0	.0176	5.70	.449	1.176	1.625
63	77.7	310.0	280.0	903.2	1183.2	.0176	5.63	.451	1.173	1.624
64	78.7	310.9	280.9	902.6	1183.5	.0176	5.56	.452	1.171	1.623
65	79.7	311.8	281.8	901.9	1183.7	.0176	5.50	.453	1.169	1.622
66	80.7	312.7	282.8	901.2	1184.0	.0176	5.43	.454	1.167	1.621
67	81.7	313.5	283.7	900.5	1184.2	.0176	5.37	.455	1.165	1.620
68	82.7	314.3	284.5	900.0	1184.5	.0176	5.31	.456	1.163	1.619
69	83.7	315.2	285.3	899.4	1184.7	.0176	5.25	.458	1.160	1.618
70	84.7	316.0	286.2	898.8	1185.0	.0176	5.19	.459	1.158	1.617
71	85.7	316.9	287.2	898.0	1185.2	.0176	5.13	.460	1.156	1.616
72	86.7	317.7	288.0	897.5	1185.5	.0176	5.08	.461	1.154	1.615
73	87.7	318.5	288.7	897.0	1185.7	.0177	5.02	.462	1.152	1.614
74	88.7	319.3	289.4	896.5	1185.9	.0177	4.97	.463	1.150	1.613
75	89.7	320.1	290.3	895.8	1186.1	.0177	4.92	.464	1.148	1.612
76	90.7	320.9	291.2	895.1	1186.3	.0177	4.87	.465	1.146	1.611
77	91.7	321.7	292.0	894.5	1186.5	.0177	4.82	.466	1.145	1.611
78	92.7	322.4	292.9	893.9	1186.8	.0177	4.77	.467	1.143	1.610
79	93.7	323.2	293.7	893.3	1187.0	.0177	4.72	.468	1.141	1.609
80	94.7	323.9	294.5	892.7	1187.2	.0177	4.67	.469	1.139	1.608
81	95.7	324.7	295.3	892.1	1187.4	.0177	4.63	.470	1.137	1.607
82	96.7	325.5	296.1	891.5	1187.6	.0177	4.58	.471	1.135	1.606
83	97.7	326.2	296.8	890.9	1187.7	.0177	4.53	.472	1.133	1.605
84	98.7	326.9	297.6	890.3	1187.9	.0177	4.49	.473	1.132	1.605
85	99.7	327.7	298.3	889.8	1188.1	.0177	4.45	.474	1.130	1.604
86	100.7	328.4	299.1	889.2	1188.3	.0178	4.41	.475	1.128	1.603
87	101.7	329.1	299.8	888.7	1188.5	.0178	4.37	.476	1.126	1.602
88	102.7	329.9	300.6	888.1	1188.7	.0178	4.33	.477	1.124	1.601
89	103.7	330.5	301.3	887.5	1188.8	.0178	4.29	.478	1.123	1.601
90	104.7	331.2	302.1	887.0	1189.1	.0178	4.25	.479	1.121	1.600

TABLE I. THE PROPERTIES OF SATURATED STEAM AND
WATER—*continued*

PRESSURE: lb./sq.in.		Temper- ature °F.	HEAT: B.t.u./lb.			VOLUME: cu.ft./lb.		ENTROPY: B.t.u./deg.F.Abs./lb.		
<i>gauge</i>	<i>Absolute</i>		<i>Sensible</i>	<i>Latent</i>	<i>Total</i>	<i>Liquid</i>	<i>Vapour</i>	<i>Liquid</i>	<i>Evap.</i>	<i>Total</i>
91	105.7	331.9	302.8	886.4	1189.2	·0178	4.21	·480	1.119	1.599
92	106.7	332.6	303.5	885.8	1189.3	·0178	4.17	·480	1.118	1.598
93	107.7	333.3	304.2	885.3	1189.5	·0178	4.14	·481	1.117	1.598
94	108.7	333.9	304.9	884.8	1189.7	·0178	4.10	·482	1.115	1.597
95	109.7	334.6	305.6	884.2	1189.8	·0178	4.07	·483	1.113	1.596
96	110.7	335.3	306.3	883.7	1190.0	·0178	4.03	·484	1.111	1.595
97	111.7	335.9	307.0	883.2	1190.2	·0178	4.00	·485	1.110	1.595
98	112.7	336.6	307.7	882.6	1190.3	·0178	3.96	·486	1.108	1.594
99	113.7	337.3	308.3	882.2	1190.5	·0178	3.93	·486	1.107	1.593
100	114.7	337.9	309.0	881.6	1190.6	·0178	3.90	·487	1.105	1.592
102	116.7	339.2	310.3	880.6	1190.9	·0178	3.83	·489	1.102	1.591
104	118.7	340.5	311.6	879.6	1191.2	·0179	3.77	·491	1.099	1.590
106	120.7	341.7	313.0	878.5	1191.5	·0179	3.71	·492	1.096	1.588
108	122.7	343.0	314.3	877.5	1191.8	·0179	3.65	·494	1.093	1.587
110	124.7	344.2	315.5	876.5	1192.0	·0179	3.60	·495	1.091	1.586
112	126.7	345.4	316.8	875.5	1192.3	·0179	3.54	·497	1.087	1.584
114	128.7	346.5	318.0	874.5	1192.5	·0179	3.49	·499	1.084	1.583
116	130.7	347.7	319.3	873.5	1192.8	·0179	3.44	·500	1.082	1.582
118	132.7	348.9	320.5	872.5	1193.0	·0180	3.39	·502	1.079	1.581
120	134.7	350.1	321.8	871.5	1193.3	·0180	3.34	·503	1.076	1.579
122	136.7	351.2	322.9	870.8	1193.6	·0180	3.30	·505	1.073	1.578
124	138.7	352.3	324.1	869.8	1193.9	·0180	3.25	·506	1.071	1.577
126	140.7	353.4	325.2	868.9	1194.1	·0180	3.21	·508	1.068	1.576
128	142.7	354.5	326.4	867.9	1194.3	·0180	3.16	·509	1.066	1.575
130	144.7	355.6	327.6	866.9	1194.5	·0180	3.12	·510	1.063	1.573
132	146.7	356.7	328.8	865.9	1194.7	·0180	3.08	·512	1.060	1.572
134	148.7	357.8	330.0	865.0	1195.0	·0180	3.04	·513	1.058	1.571
136	150.7	358.8	331.1	864.1	1195.2	·0181	3.00	·514	1.056	1.570
138	152.7	359.9	332.2	863.3	1195.5	·0181	2.96	·516	1.053	1.569
140	154.7	360.9	333.2	862.5	1195.7	·0181	2.93	·517	1.051	1.568
142	156.7	361.9	334.3	861.6	1195.9	·0181	2.89	·518	1.049	1.567
144	158.7	362.9	335.4	860.7	1196.1	·0181	2.86	·520	1.046	1.566
146	160.7	364.0	336.4	859.9	1196.3	·0181	2.82	·521	1.044	1.565
148	162.7	365.0	337.5	858.9	1196.4	·0182	2.79	·522	1.042	1.564
150	164.7	365.9	338.6	858.0	1196.6	·0182	2.76	·523	1.040	1.563
155	169.7	368.3	341.1	856.0	1197.1	·0182	2.68	·526	1.034	1.560
160	174.7	370.7	343.6	853.9	1197.5	·0182	2.61	·529	1.029	1.558
165	179.7	372.9	346.1	851.8	1197.9	·0183	2.54	·532	1.024	1.556
170	184.7	375.2	348.5	849.8	1198.3	·0183	2.48	·535	1.018	1.553
175	189.7	377.5	350.9	847.9	1198.8	·0183	2.41	·538	1.013	1.551
180	194.7	379.6	353.2	845.9	1199.1	·0184	2.35	·540	1.009	1.549
185	199.7	381.6	355.4	844.1	1199.5	·0184	2.30	·543	1.004	1.547
190	204.7	383.7	357.6	842.2	1199.8	·0184	2.24	·546	·999	1.545
195	209.7	385.7	359.9	840.2	1200.1	·0184	2.18	·548	·995	1.543
200	214.7	387.7	362.0	838.4	1200.4	·0185	2.14	·551	·990	1.541

TABLE I. THE PROPERTIES OF SATURATED STEAM AND
WATER—continued

PRESSURE: <i>lb./sq.in.</i>		<i>Temper- ature °F.</i>	HEAT: <i>B.t.u./lb.</i>			VOLUME: <i>cu.ft./lb.</i>		ENTROPY: <i>B.t.u./deg.F.Abs./lb.</i>		
<i>gauge</i>	<i>Absolute</i>		<i>Sensible</i>	<i>Latent</i>	<i>Total</i>	<i>Liquid</i>	<i>Vapour</i>	<i>Liquid</i>	<i>Evap.</i>	<i>Total</i>
210	224.7	391.7	366.2	834.8	1201.0	.0185	2.04	.556	.981	1.537
220	234.7	395.5	370.3	831.2	1201.5	.0186	1.96	.561	.972	1.533
230	244.7	399.1	374.2	827.8	1202.0	.0186	1.88	.565	.964	1.529
240	254.7	402.7	378.0	824.5	1202.5	.0186	1.81	.570	.956	1.526
250	264.7	406.1	381.7	821.2	1202.9	.0187	1.74	.574	.947	1.523
260	274.7	409.3	385.3	817.9	1203.2	.0187	1.68	.578	.941	1.519
270	284.7	412.5	388.8	814.8	1203.6	.0188	1.62	.582	.934	1.516
280	294.7	415.8	392.3	811.6	1203.9	.0188	1.57	.586	.927	1.513
290	304.7	418.8	395.7	808.5	1204.2	.0189	1.52	.590	.920	1.510
300	314.7	421.7	398.9	805.5	1204.4	.0189	1.47	.593	.914	1.507
310	324.7	424.7	402.1	802.6	1204.7	.0190	1.43	.597	.908	1.505
320	334.7	427.5	405.2	799.7	1204.9	.0191	1.39	.601	.901	1.502
330	344.7	430.3	408.3	796.7	1205.0	.0191	1.35	.604	.895	1.499
340	354.7	433.0	411.3	793.8	1205.1	.0191	1.31	.607	.890	1.497
350	364.7	435.7	414.3	791.0	1205.3	.0192	1.27	.611	.883	1.494
360	374.7	438.3	417.2	788.2	1205.4	.0192	1.24	.614	.878	1.492
370	384.7	440.8	420.0	785.4	1205.4	.0193	1.21	.617	.872	1.489
380	394.7	443.3	422.8	782.7	1205.5	.0193	1.18	.620	.867	1.487
390	404.7	445.7	425.6	779.9	1205.5	.0194	1.15	.623	.862	1.485
400	414.7	448.1	428.2	777.4	1205.6	.0194	1.12	.626	.856	1.482
410	424.7	450.5	430.8	774.8	1205.6	.0195	1.09	.629	.851	1.480
420	434.7	452.8	433.4	772.2	1205.6	.0195	1.07	.632	.846	1.478
430	444.7	455.1	436.0	769.6	1205.6	.0195	1.04	.635	.841	1.476
440	454.7	457.3	438.5	767.1	1205.6	.0196	1.02	.637	.837	1.474
450	464.7	459.5	441.0	764.5	1205.5	.0196	1.00	.640	.832	1.472
460	474.7	461.7	443.4	762.1	1205.5	.0196	.979	.643	.827	1.470
470	484.7	463.8	445.9	759.5	1205.4	.0197	.959	.645	.823	1.468
480	494.7	465.9	448.3	757.1	1205.4	.0197	.939	.648	.818	1.466
490	504.7	467.9	450.6	754.7	1205.3	.0198	.920	.650	.814	1.464
500	514.7	470.0	453.0	752.3	1205.3	.0198	.902	.653	.809	1.462
510	524.7	472.0	455.3	749.9	1205.2	.0199	.885	.655	.805	1.460
520	534.7	474.0	457.6	747.5	1205.1	.0199	.868	.657	.801	1.458
530	544.7	475.9	459.8	745.2	1205.0	.0199	.852	.660	.796	1.456
540	554.7	477.8	462.0	742.8	1204.8	.0200	.835	.662	.792	1.454
550	564.7	479.7	464.2	740.5	1204.7	.0200	.820	.664	.789	1.453
560	574.7	481.6	466.4	738.1	1204.5	.0200	.805	.667	.784	1.451
570	584.7	483.4	468.6	735.8	1204.4	.0201	.791	.669	.780	1.449
580	594.7	485.2	470.7	733.5	1204.2	.0201	.776	.671	.776	1.447
590	604.7	487.0	472.8	731.3	1204.1	.0201	.763	.673	.773	1.446
600	614.7	488.8	474.8	729.1	1203.9	.0202	.750	.676	.768	1.444
610	624.7	490.5	476.9	726.8	1203.7	.0202	.738	.678	.764	1.442
620	634.7	492.3	479.0	724.5	1203.5	.0203	.726	.680	.761	1.441
630	644.7	494.0	481.0	722.3	1203.3	.0203	.714	.682	.757	1.439
640	654.7	495.7	483.0	720.1	1203.1	.0203	.703	.684	.754	1.438
650	664.7	497.3	484.9	718.0	1202.9	.0204	.692	.686	.750	1.436

TABLE I. THE PROPERTIES OF SATURATED STEAM AND
WATER—*continued*

PRESSURE: lb./sq.in.		Temper- ature °F.	HEAT: B.t.u./lb.			VOLUME: cu.ft./lb.		ENTROPY: B.t.u./deg.F. Abs./lb.		
<i>gauge</i>	<i>Absolute</i>		<i>Sensible</i>	<i>Latent</i>	<i>Total</i>	<i>Liquid</i>	<i>Vapour</i>	<i>Liquid</i>	<i>Evap.</i>	<i>Total</i>
660	674.7	499.0	486.9	715.8	1202.7	.0204	.681	.668	.747	1.435
670	684.7	500.6	488.8	713.7	1202.5	.0204	.670	.690	.743	1.433
680	694.7	502.2	490.7	711.5	1202.2	.0205	.660	.692	.740	1.432
690	704.7	503.9	492.6	709.4	1202.0	.0205	.650	.694	.736	1.430
700	714.7	505.4	494.4	707.4	1201.8	.0206	.641	.696	.733	1.429
710	724.7	507.0	496.3	705.2	1201.5	.0206	.632	.697	.730	1.427
720	734.7	508.5	498.2	703.1	1201.3	.0206	.623	.699	.727	1.426
730	744.7	510.0	500.0	701.0	1201.0	.0207	.614	.701	.723	1.424
740	754.7	511.5	501.9	698.9	1200.8	.0207	.605	.703	.720	1.423
750	764.7	513.0	503.8	696.7	1200.5	.0208	.596	.705	.716	1.421
760	774.7	514.5	505.5	694.7	1200.2	.0208	.588	.707	.713	1.420
770	784.7	516.0	507.2	692.8	1200.0	.0208	.580	.708	.711	1.419
780	794.7	517.5	509.0	690.7	1199.7	.0209	.572	.710	.707	1.417
790	804.7	518.9	510.8	688.6	1199.4	.0209	.564	.712	.704	1.416
800	814.7	520.3	512.5	686.6	1199.1	.0209	.557	.714	.700	1.414
850	864.7	526.9	521.0	676.5	1197.5	.0211	.522	.722	.686	1.408
900	914.7	533.9	529.2	666.7	1195.9	.0213	.490	.730	.671	1.401
950	964.7	540.3	537.1	656.9	1194.0	.0215	.462	.738	.657	1.395
1000	1014.7	546.4	544.8	647.2	1192.0	.0217	.437	.745	.644	1.389
1050	1064.7	552.3	552.3	637.8	1190.0	.0218	.414	.753	.630	1.383
1100	1114.7	557.9	559.6	628.3	1187.9	.0220	.394	.760	.617	1.377
1150	1164.7	563.4	566.7	619.0	1185.7	.0222	.375	.766	.606	1.372
1200	1214.7	568.8	573.8	609.6	1183.4	.0223	.357	.773	.593	1.366
1250	1264.7	573.9	580.8	600.2	1181.0	.0225	.341	.780	.581	1.361
1300	1314.7	578.9	587.6	590.9	1178.5	.0227	.325	.786	.569	1.355
1350	1364.7	583.7	594.2	581.8	1176.0	.0229	.311	.792	.558	1.350
1400	1414.7	588.4	600.7	572.6	1173.3	.0231	.298	.798	.547	1.345
1450	1464.7	593.0	607.2	563.3	1170.5	.0233	.285	.804	.536	1.340
1500	1514.7	597.5	613.6	554.2	1167.8	.0235	.274	.810	.525	1.335
1550	1564.7	601.8	619.8	545.2	1165.0	.0237	.264	.816	.514	1.330
1600	1614.7	606.1	626.0	536.0	1162.0	.0239	.254	.821	.503	1.324
1700	1714.7	614.3	638.1	517.7	1155.8	.0243	.234	.832	.482	1.314
1800	1814.7	622.1	650.0	499.0	1149.1	.0248	.215	.843	.461	1.304
1900	1914.7	629.6	661.8	480.4	1142.2	.0253	.200	.853	.441	1.294
2000	2014.7	636.8	673.5	461.5	1135.0	.0258	.186	.863	.421	1.284
2100	2114.7	643.7	685.1	442.0	1127.1	.0263	.173	.874	.400	1.274
2200	2214.7	650.3	696.8	422.1	1118.9	.0268	.161	.884	.380	1.264
2300	2314.7	656.8	708.5	401.5	1110.0	.0274	.150	.894	.360	1.253
2400	2414.7	663.0	720.3	380.2	1100.5	.0281	.139	.904	.338	1.242
2500	2514.7	669.0	732.5	357.6	1090.1	.0289	.129	.914	.317	1.231
2600	2614.7	674.8	744.9	333.7	1078.6	.0297	.120	.925	.296	1.220
2700	2714.7	680.4	758.2	308.0	1066.2	.0306	.111	.935	.272	1.207
2800	2814.7	685.8	772.3	279.2	1051.5	.0318	.102	.947	.244	1.191
2900	2914.7	691.0	787.5	246.9	1034.4	.0332	.0936	.960	.215	1.175
3000	3014.7	696.1	805.3	207.4	1012.7	.0349	.0847	.975	.180	1.155
3193*	3208*	705.6*	896.0*	0	896.0*	.0489*	.0489*	1.052*	0	1.052*

* The values at the critical point were obtained by extrapolation.

TABLE II THE PROPERTIES OF SUPERHEATED STEAM

PRESSURE	in. Hg. vacuum	lb./sq.ft. Abs. (Sat. temp. °F.)	VOLUME: cu.ft./lb. } at temperatures shown:— TOTAL HEAT: B.t.u./lb. ENTROPY: B.t.u./deg.F./lb.																	
			Sat.	110°F.	120°F.	130°F.	140°F.	150°F.	160°F.	170°F.	180°F.	190°F.	200°F.	220°F.	240°F.	260°F.	280°F.	300°F.	350°F.	400°F.
28		-979 (101)	341 1105.7 1.980	346 1110.3 1.987	352 1115.1 1.995	358 1119.6 2.003	364 1124.1 2.011	370 1128.6 2.018	376 1133.1 2.025	382 1137.6 2.033	388 1142.2 2.040	394 1146.7 2.046	400 1151.2 2.053	413 1160.4 2.068	425 1169.5 2.081	437 1178.5 2.094	450 1187.6 2.107	462 1196.7 2.119	492 1219.7 2.149	522 1242.4 2.176
			276 1109.0 1.961	—	281 1114.6 1.972	286 1119.4 1.980	291 1124.0 1.988	296 1128.4 1.995	301 1133.0 2.003	306 1137.5 2.010	311 1142.1 2.017	315 1146.5 2.024	320 1151.1 2.031	330 1160.2 2.045	340 1169.2 2.058	350 1178.5 2.072	359 1187.5 2.085	369 1196.7 2.097	393 1219.7 2.126	418 1242.3 2.154
27		-1.469 (114.9)	233 1111.8 1.946	—	235 1114.8 1.951	239 1119.3 1.959	243 1123.8 1.967	247 1128.3 1.974	251 1132.8 1.982	255 1137.3 1.990	259 1141.8 1.997	263 1146.4 2.005	267 1151.0 2.011	275 1160.1 2.025	283 1169.1 2.039	291 1178.4 2.051	299 1187.4 2.065	308 1196.6 2.078	328 1219.6 2.106	348 1242.3 2.134
			201 1114.1 1.933	—	—	204 1119.2 1.942	208 1123.7 1.950	211 1128.2 1.957	215 1132.7 1.964	218 1137.2 1.971	222 1141.8 1.978	225 1146.2 1.986	229 1150.8 1.993	236 1160.0 2.007	243 1169.0 2.020	250 1178.3 2.033	257 1187.4 2.047	263 1196.6 2.060	281 1219.6 2.089	298 1242.3 2.116
26		-1.958 (125.3)	177 1116.0 1.922	—	—	179 1119.0 1.926	182 1123.6 1.934	185 1128.0 1.941	188 1132.6 1.949	191 1137.0 1.956	194 1141.7 1.963	197 1146.1 1.970	200 1150.7 1.977	206 1159.9 1.991	213 1168.9 2.005	219 1178.2 2.018	225 1187.3 2.030	231 1196.5 2.044	246 1219.5 2.072	261 1242.2 2.100
			Sat.	140°F.	150°F.	160°F.	170°F.	180°F.	190°F.	200°F.	210°F.	220°F.	230°F.	240°F.	250°F.	300°F.	350°F.	400°F.	450°F.	500°F.	550°F.
25		-2.448 (133.6)	144 1119.6 1.904	145 1123.1 1.908	148 1127.7 1.916	150 1132.2 1.923	153 1136.8 1.931	155 1141.4 1.938	158 1145.9 1.945	160 1150.5 1.952	162 1155.0 1.959	165 1159.7 1.966	167 1164.3 1.973	170 1168.8 1.979	172 1173.5 1.986	184 1196.4 2.019	197 1219.4 2.048	209 1242.2 2.075	221 1265.2 2.101	233 1286.7 2.126
			121 1122.6 1.889	—	123 1127.4 1.896	125 1132.0 1.903	127 1136.4 1.911	129 1141.1 1.918	131 1145.6 1.925	133 1150.2 1.932	135 1154.7 1.939	137 1159.5 1.946	139 1164.1 1.953	141 1168.6 1.959	143 1173.3 1.966	154 1196.3 1.998	164 1219.4 2.028	174 1242.1 2.055	184 1265.2 2.082	194 1286.6 2.106
24		-2.938 (140.7)	105 1125.0 1.876	—	105 1127.0 1.878	107 1131.6 1.885	109 1136.1 1.893	111 1140.8 1.900	112 1145.3 1.907	114 1150.0 1.914	116 1154.5 1.921	118 1159.2 1.928	119 1163.9 1.935	121 1168.4 1.942	123 1173.2 1.949	132 1196.2 1.981	140 1219.2 2.011	149 1242.0 2.038	158 1265.1 2.064	167 1286.5 2.090
			92.6 1127.2 1.865	—	—	93.6 1131.3 1.870	95.2 1135.9 1.878	96.7 1140.5 1.885	98.2 1145.1 1.892	99.7 1149.8 1.900	101 1154.3 1.907	103 1159.0 1.914	105 1163.7 1.921	106 1168.3 1.928	108 1173.0 1.935	115 1196.2 1.966	123 1219.1 1.996	131 1242.0 2.023	138 1265.0 2.050	146 1286.5 2.075
23		-3.428 (146.8)	105 1125.0 1.876	—	—	107 1131.6 1.885	109 1136.1 1.893	111 1140.8 1.900	112 1145.3 1.907	114 1150.0 1.914	116 1154.5 1.921	118 1159.2 1.928	119 1163.9 1.935	121 1168.4 1.942	123 1173.2 1.949	132 1196.2 1.981	140 1219.2 2.011	149 1242.0 2.038	158 1265.1 2.064	167 1286.5 2.090
			92.6 1127.2 1.865	—	—	93.6 1131.3 1.870	95.2 1135.9 1.878	96.7 1140.5 1.885	98.2 1145.1 1.892	99.7 1149.8 1.900	101 1154.3 1.907	103 1159.0 1.914	105 1163.7 1.921	106 1168.3 1.928	108 1173.0 1.935	115 1196.2 1.966	123 1219.1 1.996	131 1242.0 2.023	138 1265.0 2.050	146 1286.5 2.075
22		-3.917 (152.1)	92.6 1127.2 1.865	—	—	93.6 1131.3 1.870	95.2 1135.9 1.878	96.7 1140.5 1.885	98.2 1145.1 1.892	99.7 1149.8 1.900	101 1154.3 1.907	103 1159.0 1.914	105 1163.7 1.921	106 1168.3 1.928	108 1173.0 1.935	115 1196.2 1.966	123 1219.1 1.996	131 1242.0 2.023	138 1265.0 2.050	146 1286.5 2.075
			82.9 1129.1 1.865	—	—	83.2 1131.0 1.867	84.6 1135.6 1.874	86.0 1140.2 1.882	87.3 1144.8 1.879	88.7 1149.5 1.886	90.1 1154.0 1.893	91.5 1158.8 1.900	92.9 1163.5 1.907	94.2 1168.1 1.915	95.6 1172.9 1.922	102 1196.1 1.953	109 1219.0 1.982	116 1241.9 2.010	123 1265.0 2.036	130 1286.5 2.062

TABLE II. THE PROPERTIES OF SUPERHEATED STEAM—continued

PRESSURE			VOLUME: cu.ft./lb. } at temperatures shown: — TOTAL HEAT: B.t.u./lb. ENTROPY: B.t.u./deg.F./lb.																
in. Hg. vacuum	lb./sq.in. Abs. (Sat. temp. °F.)		170°F.	180°F.	190°F.	200°F.	210°F.	220°F.	230°F.	240°F.	260°F.	280°F.	300°F.	320°F.	340°F.	360°F.	380°F.	400°F.	500°F.
20	4-896 (161-4)	75-1 1131-0 1-847	76-1 1135-3 1-853	77-3 1139-9 1-860	78-6 1144-6 1-867	79-8 1149-2 1-874	81-0 1153-8 1-881	82-2 1158-6 1-889	83-5 1163-3 1-896	84-7 1168-0 1-903	87-2 1177-4 1-916	89-6 1186-6 1-929	92-1 1196-0 1-941	94-5 1205-2 1-954	97-0 1214-3 1-966	99-4 1223-6 1-977	102 1232-7 1-988	104 1241-8 1-999	117 1288-4 2-050
19	5-386 (165-4)	68-7 1132-7 1-839	69-2 1135-0 1-842	70-3 1139-6 1-849	71-4 1144-3 1-856	72-5 1149-0 1-864	73-6 1153-6 1-871	74-8 1158-4 1-878	75-9 1163-1 1-885	77-0 1167-8 1-892	79-3 1177-2 1-905	81-5 1186-5 1-918	83-7 1195-9 1-930	85-9 1205-1 1-943	88-2 1214-3 1-955	90-4 1223-5 1-966	92-6 1232-6 1-977	94-8 1241-7 1-988	106 1288-4 2-039
18	5-876 (169-2)	63-3 1134-2 1-832	— — —	64-4 1139-3 1-839	65-5 1144-0 1-847	66-5 1148-8 1-854	67-5 1153-4 1-861	68-5 1158-1 1-868	69-6 1162-9 1-875	70-6 1167-6 1-882	72-7 1177-0 1-895	74-7 1186-3 1-908	76-7 1195-8 1-921	78-8 1205-0 1-934	80-8 1214-2 1-945	82-8 1223-4 1-956	84-9 1232-5 1-967	86-9 1241-7 1-978	97-1 1288-3 2-029
17	6-365 (172-7)	58-8 1135-6 1-825	— — —	59-2 1139-0 1-830	60-1 1143-8 1-838	61-1 1148-5 1-845	62-0 1153-2 1-852	63-0 1157-9 1-859	63-9 1162-7 1-866	64-9 1167-4 1-873	66-8 1176-8 1-886	68-7 1186-2 1-899	70-6 1195-6 1-912	72-4 1204-9 1-924	74-3 1214-1 1-936	76-2 1223-3 1-947	78-1 1232-4 1-958	80-0 1241-6 1-968	89-4 1288-2 2-020
16	6-855 (175-9)	54-8 1136-9 1-819	— — —	55-5 1138-7 1-822	56-4 1143-5 1-829	57-3 1148-0 1-837	58-2 1153-0 1-844	59-1 1157-7 1-851	60-0 1162-5 1-858	60-9 1167-3 1-865	62-7 1176-7 1-878	64-5 1186-1 1-891	66-2 1195-5 1-904	68-0 1204-8 1-916	69-8 1214-0 1-928	71-6 1223-3 1-939	73-3 1232-4 1-950	75-1 1241-5 1-960	83-9 1288-2 2-012
15	7-344 (178-9)	51-4 1138-1 1-813	52-2 1143-2 1-821	53-0 1148-0 1-829	53-8 1152-8 1-836	54-7 1157-5 1-843	55-5 1162-3 1-850	56-4 1167-1 1-857	57-2 1171-9 1-864	58-0 1176-6 1-871	59-7 1186-0 1-883	61-3 1195-4 1-896	63-0 1204-7 1-908	64-6 1213-9 1-920	66-2 1223-2 1-932	67-9 1232-3 1-943	69-5 1241-5 1-953	73-6 1264-7 1-980	77-7 1288-1 2-005
14	7-834 (181-9)	48-4 1139-2 1-808	48-9 1143-0 1-814	49-7 1147-8 1-821	50-4 1152-6 1-829	51-2 1157-3 1-836	52-0 1162-1 1-843	52-8 1167-0 1-850	53-6 1171-7 1-857	54-4 1176-4 1-863	55-9 1185-8 1-876	57-4 1195-3 1-889	59-0 1204-6 1-901	60-5 1213-8 1-913	62-1 1223-1 1-925	63-6 1232-2 1-936	65-2 1241-4 1-946	69-0 1264-6 1-972	72-8 1288-1 1-997
13	8-324 (184-7)	45-7 1140-4 1-803	46-0 1145-7 1-807	46-8 1147-5 1-815	47-5 1149-2 1-822	48-2 1151-7 1-829	48-9 1154-2 1-836	49-7 1156-8 1-843	50-4 1159-3 1-850	51-2 1161-8 1-857	52-6 1169-2 1-870	54-1 1176-7 1-882	55-5 1184-1 1-894	57-0 1193-4 1-906	58-4 1202-6 1-918	59-9 1211-8 1-929	61-3 1221-0 1-939	64-9 1246-6 1-965	68-5 1268-0 1-990
12	8-813 (187-3)	43-3 1141-4 1-798	43-4 1145-4 1-801	44-1 1147-2 1-808	44-8 1152-2 1-815	45-5 1157-1 1-822	46-2 1162-0 1-830	46-9 1166-6 1-837	47-6 1171-4 1-844	48-3 1176-3 1-850	49-6 1185-6 1-863	51-0 1195-1 1-876	52-4 1204-4 1-888	53-8 1213-6 1-900	55-1 1222-9 1-912	56-5 1232-1 1-923	57-9 1241-2 1-933	61-3 1264-5 1-959	64-6 1288-0 1-984
11	9-303 (189-8)	41-2 1142-5 1-794	— — —	41-8 1147-0 1-802	42-4 1152-0 1-809	43-1 1157-0 1-816	43-8 1162-0 1-823	44-4 1166-4 1-831	45-1 1171-2 1-838	45-7 1176-0 1-845	47-0 1185-5 1-858	48-3 1195-0 1-870	49-6 1204-3 1-882	50-9 1213-6 1-894	52-2 1222-8 1-906	53-5 1231-9 1-917	54-8 1241-2 1-927	58-1 1264-4 1-954	61-2 1287-9 1-978

TABLE II. THE PROPERTIES OF SUPERHEATED STEAM—continued

PRESSURE		VOLUME: cu. ft./lb. } at temperatures shown:— TOTAL HEAT: B.t.u./lb. } ENTROPY: B.t.u./deg. F./lb. }																
in. Hg. vacuum	lb. sq. in. Abs. (Sat. temp. ° F.)	200° F.	210° F.	220° F.	230° F.	240° F.	250° F.	260° F.	280° F.	300° F.	320° F.	340° F.	360° F.	380° F.	400° F.	450° F.	500° F.	600° F.
10	9.793 (192.2)	39.2 1143.4 1.790	40.3 1151.8 1.804	40.9 1156.5 1.811	41.5 1161.5 1.818	42.2 1166.3 1.825	42.8 1171.1 1.832	43.4 1175.8 1.839	44.7 1185.3 1.852	45.9 1194.8 1.864	47.1 1204.2 1.876	48.4 1213.5 1.888	49.6 1222.7 1.900	50.8 1231.8 1.911	52.1 1241.1 1.921	55.1 1264.4 1.948	58.2 1287.9 1.973	64.3 1335.8 2.020
9	10.28 (194.5)	37.5 1143.6 1.786	38.4 1151.6 1.798	39.0 1156.3 1.805	39.6 1161.3 1.812	40.2 1166.1 1.819	40.8 1170.9 1.826	41.3 1175.6 1.833	42.5 1185.2 1.846	43.7 1194.7 1.858	44.9 1204.1 1.870	46.1 1213.4 1.882	47.3 1222.6 1.894	48.4 1231.7 1.905	49.6 1241.0 1.916	52.5 1264.3 1.942	55.4 1287.8 1.967	61.2 1335.8 2.015
8	10.77 (196.8)	35.9 1145.2 1.782	36.6 1151.4 1.793	37.2 1156.1 1.800	37.7 1161.1 1.807	38.3 1166.0 1.814	38.9 1170.8 1.821	39.4 1175.5 1.828	40.6 1185.0 1.841	41.7 1194.6 1.853	42.8 1203.8 1.865	44.0 1213.2 1.877	45.1 1222.5 1.889	46.2 1231.6 1.900	47.3 1240.9 1.911	50.2 1264.2 1.936	52.9 1287.8 1.962	58.4 1335.8 2.010
7	11.26 (198.9)	34.4 1146.1 1.779	35.0 1151.2 1.788	35.6 1156.9 1.795	36.1 1160.9 1.802	36.6 1165.8 1.809	37.2 1170.6 1.816	37.7 1175.4 1.822	38.8 1184.9 1.835	39.9 1194.4 1.848	41.0 1203.8 1.860	42.1 1213.1 1.872	43.1 1222.4 1.884	44.2 1231.6 1.895	45.3 1240.9 1.905	48.0 1264.2 1.932	50.6 1287.7 1.957	55.9 1335.7 2.005
6	11.75 (201.0)	— 1146.8 1.775	— 1151.0 1.782	34.0 1155.8 1.790	34.6 1160.8 1.797	35.1 1165.6 1.804	35.6 1170.4 1.811	36.1 1175.2 1.818	37.2 1184.7 1.830	38.2 1194.3 1.843	39.3 1203.7 1.855	40.3 1213.0 1.867	41.3 1222.3 1.879	42.4 1231.5 1.890	43.4 1240.8 1.901	46.0 1264.1 1.927	48.5 1287.7 1.952	53.6 1335.7 2.000
5	12.24 (203.0)	31.9 1147.5 1.772	32.7 1150.8 1.785	33.2 1160.6 1.792	33.7 1165.5 1.799	34.2 1170.3 1.806	34.7 1175.0 1.813	35.2 1179.9 1.819	35.7 1184.6 1.826	36.2 1189.4 1.832	36.7 1194.2 1.839	37.7 1203.6 1.851	38.7 1212.9 1.863	39.7 1222.2 1.874	40.6 1231.4 1.885	41.6 1240.7 1.896	46.5 1287.6 1.948	51.4 1335.7 1.996
4	12.73 (204.9)	30.7 1148.2 1.769	30.9 1150.7 1.781	31.9 1160.4 1.788	32.4 1165.3 1.795	32.8 1170.1 1.802	33.3 1174.9 1.808	33.8 1179.8 1.814	34.3 1184.4 1.821	34.8 1189.2 1.828	35.3 1194.0 1.835	36.2 1203.5 1.846	37.2 1212.8 1.858	38.1 1222.1 1.870	39.1 1231.3 1.881	40.0 1240.7 1.892	44.7 1287.6 1.944	49.4 1335.6 1.991
3	13.22 (206.8)	29.7 1148.8 1.766	29.8 1150.5 1.776	30.7 1160.3 1.783	31.1 1165.2 1.790	31.6 1170.0 1.797	32.1 1174.7 1.804	32.6 1179.6 1.811	33.0 1184.2 1.817	33.5 1189.0 1.824	33.9 1193.8 1.830	34.9 1203.4 1.842	35.8 1212.7 1.854	36.7 1222.0 1.865	37.6 1231.2 1.876	38.5 1240.6 1.887	43.1 1287.5 1.940	47.6 1335.6 1.987
2	13.71 (208.6)	28.7 1149.5 1.763	29.1 1155.2 1.772	29.6 1160.1 1.779	30.0 1165.0 1.786	30.5 1169.8 1.793	30.9 1174.6 1.799	31.4 1179.5 1.806	31.8 1184.1 1.812	32.3 1188.9 1.819	32.7 1193.6 1.826	33.6 1203.2 1.838	34.5 1212.6 1.850	35.4 1221.9 1.861	36.3 1231.1 1.872	37.2 1240.5 1.883	41.5 1287.5 1.935	45.9 1335.5 1.983
1	14.20 (210.3)	27.7 1150.1 1.760	28.1 1155.0 1.768	28.5 1160.0 1.775	29.0 1164.8 1.782	29.4 1169.7 1.789	29.8 1174.4 1.796	30.3 1179.3 1.802	30.7 1184.0 1.808	31.2 1188.8 1.815	31.6 1193.6 1.821	32.4 1203.1 1.833	33.3 1212.5 1.845	34.2 1221.8 1.857	35.0 1231.0 1.868	35.9 1240.4 1.879	40.1 1287.4 1.931	44.3 1335.5 1.979

TABLE II. THE PROPERTIES OF SUPERHEATED STEAM—continued

PRESSURE: lb./sq. in.		VOLUME: cu. ft./lb. TOTAL HEAT: B.t.u./lb. } at temperatures shown:— ENTHALPY: B.t.u./deg. F./lb.																
gauge	Abs. temp. ° F.	Sat. 220°F. 230°F. 240°F. 250°F. 260°F. 270°F. 280°F. 290°F. 300°F. 320°F. 340°F. 360°F. 380°F. 400°F. 450°F. 500°F. 600°F.																
		26.8 1150.8 1.757	27.1 1154.9 1.764	27.6 1159.8 1.771	28.0 1164.6 1.778	28.4 1169.5 1.785	28.8 1174.3 1.791	29.2 1179.2 1.798	29.7 1183.8 1.805	30.1 1188.7 1.811	30.5 1193.5 1.818	31.3 1202.9 1.830	32.2 1212.4 1.841	33.8 1230.9 1.865	34.7 1263.7 1.875	36.7 1287.4 1.902	38.8 1310.6 1.927	42.9 1335.4 1.975
0	14.696 (212)	26.8 1150.8 1.757	27.1 1154.9 1.764	27.6 1159.8 1.771	28.0 1164.6 1.778	28.4 1169.5 1.785	28.8 1174.3 1.791	29.2 1179.2 1.798	29.7 1183.8 1.805	30.1 1188.7 1.811	30.5 1193.5 1.818	31.3 1202.9 1.830	32.2 1212.4 1.841	33.8 1230.9 1.865	34.7 1263.7 1.875	36.7 1287.4 1.902	38.8 1310.6 1.927	42.9 1335.4 1.975
1	15.7 (215.4)	25.2 1152.0 1.752	25.4 1154.6 1.757	25.8 1159.5 1.763	26.2 1164.3 1.770	26.6 1169.2 1.777	27.0 1174.0 1.784	27.4 1178.9 1.791	27.7 1183.5 1.797	28.1 1188.3 1.803	28.5 1193.2 1.810	29.3 1202.6 1.822	30.1 1212.1 1.833	31.6 1230.7 1.857	32.4 1263.2 1.868	34.3 1287.3 1.894	36.3 1310.3 1.920	40.1 1335.3 1.968
2	16.7 (218.5)	23.8 1153.2 1.747	23.8 1154.3 1.749	24.2 1159.2 1.756	24.6 1164.0 1.763	25.0 1168.8 1.770	25.3 1173.6 1.776	25.7 1178.5 1.783	26.1 1183.2 1.790	26.4 1188.0 1.796	26.8 1192.8 1.802	27.5 1202.1 1.814	28.3 1211.6 1.826	29.7 1230.5 1.850	30.5 1263.0 1.861	32.3 1287.1 1.887	34.1 1310.5 1.912	37.7 1335.2 1.960
3	17.7 (221.5)	22.5 1154.3 1.742	—	22.8 1158.9 1.749	23.2 1163.6 1.756	23.5 1168.3 1.763	23.9 1173.3 1.769	24.2 1178.2 1.776	24.6 1182.9 1.783	24.9 1187.8 1.789	25.3 1192.5 1.796	26.0 1201.7 1.808	26.7 1211.1 1.820	28.1 1230.3 1.843	28.7 1263.2 1.854	30.5 1288.1 1.881	32.2 1310.9 1.906	35.6 1335.1 1.954
4	18.7 (224.5)	21.4 1155.3 1.738	—	21.6 1158.6 1.743	21.9 1163.4 1.750	22.3 1168.2 1.757	22.6 1173.0 1.763	22.9 1177.9 1.770	23.3 1182.6 1.776	23.6 1187.4 1.783	23.9 1192.2 1.790	24.6 1201.7 1.802	25.2 1211.3 1.813	26.5 1230.1 1.837	27.2 1263.6 1.848	28.8 1288.0 1.875	30.4 1314.9 1.900	33.7 1339.3 1.948
5	19.7 (227.4)	20.4 1156.3 1.734	20.5 1158.4 1.737	20.8 1163.1 1.744	21.1 1167.9 1.751	21.4 1172.7 1.757	21.8 1177.6 1.764	22.1 1182.3 1.770	22.4 1187.1 1.777	22.7 1191.9 1.783	23.3 1201.5 1.790	23.9 1210.8 1.807	24.6 1220.4 1.819	25.8 1239.4 1.831	27.3 1262.8 1.869	28.9 1286.6 1.894	30.4 1310.6 1.919	31.9 1334.8 1.942
6	20.7 (230.0)	19.4 1157.3 1.730	—	19.8 1162.8 1.738	20.1 1167.6 1.745	20.4 1172.3 1.751	20.7 1177.3 1.758	21.0 1182.0 1.764	21.3 1186.8 1.771	21.6 1191.6 1.777	22.2 1201.2 1.790	22.8 1210.8 1.802	23.4 1220.2 1.814	24.6 1239.2 1.836	26.0 1262.8 1.863	27.5 1286.4 1.888	28.9 1310.6 1.913	30.4 1334.8 1.936
7	21.7 (232.4)	18.6 1158.2 1.726	—	18.8 1162.4 1.732	19.1 1167.3 1.739	19.4 1172.1 1.746	19.7 1177.0 1.753	20.0 1181.8 1.759	20.3 1186.6 1.766	20.6 1191.4 1.772	21.1 1201.0 1.785	21.7 1210.6 1.798	22.3 1220.0 1.808	23.4 1239.1 1.831	24.8 1262.7 1.858	26.2 1286.3 1.883	27.6 1310.5 1.908	29.0 1334.7 1.931
8	22.7 (234.8)	17.9 1159.1 1.722	—	18.0 1162.1 1.727	18.3 1167.0 1.734	18.6 1171.8 1.740	18.9 1176.8 1.747	19.1 1181.6 1.754	19.4 1186.3 1.760	19.7 1191.2 1.766	20.3 1200.8 1.779	20.8 1210.4 1.791	21.3 1219.9 1.803	22.4 1238.9 1.826	23.7 1262.6 1.852	25.1 1286.2 1.878	26.4 1310.4 1.903	27.7 1334.6 1.926
9	23.7 (237.1)	17.2 1160.0 1.719	—	17.2 1161.8 1.721	17.5 1166.8 1.728	17.8 1171.6 1.735	18.0 1176.5 1.742	18.3 1181.3 1.749	18.6 1186.1 1.756	18.8 1190.9 1.761	19.3 1200.6 1.774	19.9 1210.2 1.786	20.4 1219.7 1.798	21.4 1238.8 1.820	22.7 1262.5 1.847	24.0 1286.2 1.873	25.3 1310.4 1.897	26.5 1334.5 1.921

TABLE II. THE PROPERTIES OF SUPERHEATED STEAM—continued

PRESSURE: lb./sq. in.		gauge	Abs. (Sat. temp. °F.)	VOLUME: cu.ft./lb. } at temperatures shown:— TOTAL HEAT: B.t.u./lb. } ENTROPY: B.t.u./deg.F./lb. }																
				Sat.	250°F.	260°F.	270°F.	280°F.	290°F.	300°F.	310°F.	320°F.	330°F.	340°F.	360°F.	380°F.	400°F.	450°F.	500°F.	550°F.
10	24.7 (239.4)	16.5 1160.8 1.716	16.8 1168.5 1.723	17.0 1171.3 1.730	17.3 1176.3 1.738	17.5 1181.1 1.744	17.8 1185.9 1.750	18.1 1190.7 1.757	18.3 1195.6 1.763	18.6 1200.4 1.769	18.8 1205.2 1.775	19.1 1210.0 1.782	19.6 1219.3 1.793	20.1 1229.2 1.805	20.6 1239.6 1.816	20.6 1239.6 1.816	21.3 1250.1 1.824	23.0 1268.1 1.869	24.2 1310.2 1.893	25.5 1334.5 1.917
11	25.7 (241.6)	15.9 1161.6 1.712	16.1 1168.2 1.719	16.4 1171.1 1.726	16.6 1176.0 1.733	16.8 1180.8 1.740	17.1 1185.7 1.746	17.3 1190.5 1.753	17.6 1195.3 1.759	17.8 1200.2 1.765	18.1 1205.0 1.771	18.3 1209.8 1.777	18.8 1219.1 1.788	19.3 1229.0 1.801	19.8 1239.0 1.812	19.8 1239.0 1.812	20.9 1250.0 1.823	22.1 1268.0 1.864	23.3 1310.1 1.888	24.5 1334.4 1.912
12	26.7 (243.7)	15.3 1162.3 1.709	15.5 1168.0 1.714	15.7 1170.9 1.721	16.0 1175.8 1.728	16.2 1180.6 1.735	16.4 1185.4 1.741	16.7 1190.2 1.748	16.9 1195.1 1.754	17.2 1200.0 1.760	17.4 1204.8 1.767	17.6 1209.6 1.773	18.1 1218.9 1.785	18.5 1228.8 1.796	19.0 1238.4 1.808	19.0 1238.4 1.808	20.1 1250.0 1.823	21.3 1268.0 1.860	22.4 1310.0 1.884	23.5 1334.3 1.908
13	27.7 (245.8)	14.8 1163.0 1.706	14.9 1168.7 1.710	15.2 1170.6 1.717	15.4 1175.5 1.724	15.6 1180.4 1.731	15.8 1185.2 1.737	16.1 1190.0 1.743	16.3 1194.9 1.750	16.5 1199.8 1.756	16.8 1204.6 1.762	17.0 1209.4 1.768	17.4 1218.7 1.780	17.9 1228.7 1.792	18.3 1238.2 1.803	18.3 1238.2 1.803	19.4 1250.0 1.823	20.5 1268.0 1.856	21.6 1310.0 1.880	22.7 1334.2 1.903
14	28.7 (247.9)	14.3 1163.7 1.703	14.4 1169.4 1.706	14.6 1170.3 1.712	14.9 1175.3 1.719	15.1 1180.1 1.726	15.3 1185.0 1.733	15.5 1189.8 1.739	15.7 1194.7 1.745	15.9 1199.6 1.752	16.2 1204.4 1.758	16.4 1209.2 1.764	16.8 1218.5 1.776	17.2 1228.2 1.787	17.7 1237.8 1.799	17.7 1237.8 1.799	18.7 1250.0 1.825	19.8 1268.0 1.852	20.9 1309.9 1.875	21.9 1334.2 1.899
15	29.7 (249.8)	13.9 1164.4 1.700	14.1 1170.1 1.708	14.3 1175.0 1.715	14.6 1179.9 1.722	14.8 1184.8 1.729	15.0 1189.6 1.735	15.2 1194.5 1.741	15.4 1199.4 1.748	15.6 1204.2 1.754	15.8 1209.1 1.760	16.0 1213.9 1.766	16.2 1218.7 1.772	16.7 1228.4 1.783	17.1 1237.9 1.795	17.1 1237.9 1.795	18.1 1250.0 1.821	19.1 1268.0 1.848	20.1 1309.8 1.871	21.2 1334.1 1.895
16	30.7 (251.7)	13.4 1165.1 1.698	13.7 1169.9 1.704	13.9 1174.8 1.711	14.1 1179.7 1.718	14.3 1184.5 1.725	14.5 1189.3 1.731	14.7 1194.2 1.737	14.9 1199.2 1.744	15.1 1204.0 1.750	15.3 1208.9 1.756	15.5 1213.7 1.762	15.7 1218.5 1.768	16.1 1228.2 1.780	16.5 1237.8 1.791	16.5 1237.8 1.791	17.5 1250.0 1.818	18.5 1268.0 1.843	19.5 1309.7 1.868	20.5 1334.0 1.891
17	31.7 (253.6)	13.0 1165.7 1.696	13.2 1169.6 1.700	13.4 1174.6 1.707	13.6 1179.4 1.714	13.8 1184.3 1.721	14.0 1189.1 1.728	14.2 1194.0 1.734	14.4 1199.0 1.740	14.6 1203.8 1.746	14.8 1208.7 1.752	15.0 1213.5 1.758	15.2 1218.3 1.764	15.6 1228.0 1.776	16.0 1237.7 1.787	16.0 1237.7 1.787	17.0 1250.0 1.813	17.9 1268.0 1.836	18.9 1309.6 1.864	19.8 1334.0 1.888
18	32.7 (255.4)	12.7 1166.4 1.693	12.8 1169.4 1.697	13.0 1174.3 1.704	13.2 1179.2 1.710	13.4 1184.0 1.717	13.6 1188.9 1.724	13.8 1193.8 1.730	13.9 1198.8 1.736	14.1 1203.6 1.742	14.3 1208.5 1.749	14.5 1213.3 1.755	14.7 1218.1 1.761	15.1 1227.9 1.772	15.5 1237.5 1.784	15.5 1237.5 1.784	16.4 1250.0 1.810	17.4 1268.0 1.836	18.3 1309.5 1.861	19.2 1334.0 1.884
19	33.7 (257.2)	12.3 1167.0 1.691	12.4 1169.1 1.693	12.6 1174.0 1.700	12.8 1179.0 1.707	13.0 1183.8 1.714	13.2 1188.6 1.720	13.3 1193.6 1.726	13.5 1198.6 1.733	13.7 1203.4 1.739	13.9 1208.3 1.745	14.1 1213.1 1.751	14.3 1218.0 1.757	14.6 1227.8 1.769	15.0 1237.4 1.780	15.0 1237.4 1.780	15.9 1250.0 1.807	16.8 1268.0 1.833	17.7 1309.4 1.857	18.6 1333.8 1.881

TABLE II. THE PROPERTIES OF SUPERHEATED STEAM—continued

PRESSURE: lb./sq. in.		VOLUME: cu.ft./lb. } at temperatures shown:— TOTAL HEAT: B.t.u./lb. } ENTROPY: B.t.u./deg.F./lb. }																		
gauge	Abs. (Sat. temp. ° F.)	Sat.	270°F.	280°F.	290°F.	300°F.	310°F.	320°F.	330°F.	340°F.	350°F.	360°F.	370°F.	380°F.	400°F.	450°F.	500°F.	550°F.	600°F.	
20	34.7 (258.8)	12.0 1167.6 1.688	12.2 1178.7 1.697	12.4 1183.6 1.703	12.6 1188.4 1.710	12.8 1193.4 1.717	13.0 1198.3 1.723	13.1 1198.3 1.729	13.3 1203.2 1.735	13.5 1208.1 1.741	13.7 1213.0 1.747	13.9 1217.8 1.753	14.0 1222.7 1.759	14.2 1227.6 1.765	14.6 1237.2 1.777	15.5 1252.2 1.803	16.3 1267.3 1.829	17.2 1282.3 1.854	18.1 1297.3 1.878	
22	36.7 (262.3)	11.4 1168.7 1.684	11.5 1173.3 1.690	11.7 1178.2 1.697	11.9 1183.2 1.703	12.1 1188.1 1.710	12.2 1192.9 1.717	12.4 1197.9 1.722	12.6 1202.8 1.729	12.8 1207.8 1.735	12.9 1212.6 1.741	13.1 1217.5 1.747	13.3 1222.4 1.753	13.4 1227.3 1.759	13.8 1236.9 1.770	14.6 1251.9 1.797	15.4 1266.9 1.823	16.3 1281.9 1.848	17.1 1296.9 1.871	
24	38.7 (265.3)	10.8 1169.8 1.680	10.9 1174.8 1.683	11.1 1179.7 1.690	11.3 1184.6 1.697	11.4 1189.5 1.703	11.6 1194.4 1.710	11.8 1199.3 1.716	12.0 1204.2 1.722	12.1 1209.1 1.729	12.2 1214.0 1.735	12.4 1218.9 1.740	12.6 1223.8 1.747	12.7 1228.7 1.753	13.1 1238.3 1.764	13.9 1253.3 1.791	14.7 1268.3 1.817	15.4 1273.3 1.841	16.2 1278.3 1.865	
26	40.7 (268.3)	10.3 1170.8 1.676	10.4 1175.7 1.677	10.5 1180.6 1.684	10.7 1185.5 1.691	10.9 1190.4 1.697	11.0 1195.3 1.704	11.2 1200.2 1.710	11.3 1205.1 1.716	11.5 1210.0 1.723	11.6 1214.9 1.729	11.8 1219.8 1.735	11.9 1224.7 1.740	12.1 1229.6 1.747	12.4 1234.5 1.758	13.2 1249.5 1.785	13.9 1264.5 1.811	14.7 1279.5 1.836	15.4 1284.5 1.859	
28	42.7 (271.4)	9.87 1171.8 1.672	— — —	10.0 1176.8 1.678	10.2 1181.7 1.685	10.3 1186.6 1.692	10.5 1191.5 1.698	10.6 1196.4 1.704	10.8 1201.3 1.711	10.9 1206.2 1.717	11.1 1211.1 1.723	11.2 1216.0 1.729	11.4 1220.9 1.735	11.5 1225.8 1.741	11.8 1230.7 1.753	12.5 1245.7 1.780	13.3 1260.7 1.806	14.0 1275.7 1.830	14.7 1280.7 1.854	
30	44.7 (274.0)	9.46 1172.7 1.668	9.56 1176.3 1.673	9.71 1181.2 1.679	9.85 1186.2 1.686	10.0 1191.2 1.693	10.1 1196.2 1.699	10.3 1201.2 1.705	10.4 1206.2 1.712	10.6 1211.2 1.718	10.7 1216.1 1.724	10.9 1221.1 1.730	11.0 1226.0 1.736	11.1 1230.8 1.742	11.3 1235.8 1.747	12.0 1250.8 1.785	12.7 1265.8 1.810	13.3 1280.8 1.835	14.0 1295.8 1.859	
32	46.7 (276.7)	9.08 1173.5 1.665	9.14 1175.8 1.667	9.28 1180.8 1.674	9.42 1185.7 1.681	9.56 1190.8 1.687	9.70 1195.9 1.694	9.83 1200.8 1.700	9.98 1205.9 1.706	10.1 1210.8 1.713	10.2 1215.8 1.719	10.4 1220.7 1.725	10.5 1225.6 1.731	10.7 1230.5 1.737	10.8 1235.4 1.742	11.5 1250.4 1.780	12.1 1265.4 1.805	12.8 1280.4 1.830	13.4 1295.4 1.854	
34	48.7 (279.4)	8.73 1174.3 1.661	— — —	8.89 1180.3 1.669	9.02 1185.3 1.676	9.16 1190.3 1.682	9.29 1195.4 1.689	9.43 1200.4 1.695	9.56 1205.5 1.701	9.69 1210.6 1.708	9.82 1215.6 1.714	9.95 1220.7 1.720	10.1 1225.7 1.726	10.2 1230.6 1.732	10.3 1235.5 1.737	11.0 1250.5 1.775	11.6 1265.5 1.800	12.2 1280.5 1.825	12.9 1295.5 1.849	
36	50.7 (281.9)	8.40 1175.1 1.658	— — —	8.56 1181.8 1.664	8.69 1186.8 1.670	8.81 1191.8 1.677	8.91 1196.8 1.684	9.04 1201.8 1.690	9.17 1206.8 1.697	9.29 1211.8 1.703	9.42 1216.8 1.709	9.55 1221.8 1.715	9.67 1226.8 1.721	9.80 1231.8 1.727	9.91 1236.7 1.732	10.5 1251.7 1.769	11.1 1266.7 1.794	11.8 1281.7 1.819	12.3 1296.7 1.843	
38	52.7 (284.4)	8.11 1175.8 1.655	— — —	8.27 1182.5 1.661	8.39 1187.5 1.667	8.51 1192.5 1.674	8.61 1197.5 1.681	8.74 1202.5 1.687	8.81 1207.5 1.694	8.93 1212.5 1.700	9.06 1217.5 1.706	9.18 1222.5 1.712	9.30 1227.5 1.718	9.42 1232.5 1.724	9.54 1237.4 1.729	10.1 1252.4 1.767	10.7 1267.4 1.792	11.3 1282.4 1.817	11.9 1297.4 1.841	

TABLE II. THE PROPERTIES OF SUPERHEATED STEAM—continued

PRESSURE: lb./sq. in.		VOLUME: cu.ft./lb. TOTAL HEAT: B.t.u./lb. ENTROPY: B.t.u./deg.F./lb. } at temperatures shown:—																
gauge	Abs. (Sat. temp. °F.)	300°F.	310°F.	320°F.	330°F.	340°F.	350°F.	360°F.	370°F.	380°F.	390°F.	400°F.	420°F.	440°F.	460°F.	500°F.	550°F.	600°F.
40	54.7 (286.7)	7.83 1176.5 1.652	8.15 1180.1 1.668	8.27 1194.2 1.675	8.39 1199.3 1.681	8.51 1204.3 1.687	8.63 1209.4 1.694	8.75 1214.4 1.700	8.87 1219.4 1.706	8.98 1224.4 1.712	9.10 1229.3 1.718	9.22 1234.3 1.724	9.45 1244.2 1.735	9.69 1254.0 1.746	9.91 1263.8 1.757	10.4 1283.3 1.777	10.9 1307.6 1.802	11.5 1332.1 1.826
42	56.7 (289.0)	7.57 1177.1 1.649	7.73 1183.6 1.657	7.85 1193.8 1.670	8.08 1198.9 1.676	8.20 1204.0 1.683	8.31 1209.0 1.689	8.43 1214.1 1.696	8.54 1219.1 1.701	8.65 1224.0 1.707	8.77 1228.9 1.713	8.88 1233.8 1.719	9.10 1243.6 1.730	9.33 1253.7 1.741	9.55 1263.6 1.752	9.99 1283.1 1.773	10.5 1307.4 1.798	11.1 1332.0 1.821
44	58.7 (291.3)	7.33 1177.8 1.646	7.46 1183.2 1.652	7.68 1188.4 1.666	7.80 1193.5 1.672	7.91 1198.6 1.679	8.02 1203.6 1.685	8.13 1208.7 1.691	8.24 1213.8 1.697	8.35 1218.7 1.703	8.46 1223.8 1.709	8.57 1228.7 1.715	8.78 1238.5 1.726	9.00 1248.3 1.737	9.21 1258.5 1.748	9.64 1282.9 1.769	10.2 1307.2 1.794	10.7 1331.8 1.818
46	60.7 (293.5)	7.10 1178.4 1.644	7.20 1182.6 1.648	7.42 1187.8 1.662	7.53 1192.9 1.668	7.64 1198.0 1.675	7.75 1203.2 1.681	7.85 1208.3 1.687	7.96 1213.4 1.693	8.07 1218.4 1.698	8.17 1223.5 1.705	8.28 1228.4 1.711	8.51 1238.1 1.722	8.70 1247.8 1.733	8.90 1257.6 1.744	9.31 1282.7 1.765	9.83 1307.0 1.790	10.3 1331.7 1.814
48	62.7 (295.6)	6.89 1179.0 1.641	6.96 1185.6 1.644	7.18 1192.5 1.658	7.29 1197.8 1.664	7.39 1202.9 1.671	7.50 1208.0 1.677	7.60 1213.0 1.683	7.70 1218.1 1.689	7.80 1223.1 1.695	7.91 1228.1 1.701	8.01 1233.1 1.707	8.22 1242.9 1.718	8.42 1252.9 1.730	8.62 1262.9 1.740	9.02 1287.9 1.762	9.51 1308.8 1.786	10.0 1331.6 1.810
50	64.7 (297.7)	6.68 1179.6 1.638	6.82 1186.9 1.647	7.03 1197.4 1.661	7.13 1202.5 1.667	7.23 1207.6 1.673	7.33 1212.6 1.680	7.44 1217.8 1.686	7.54 1222.8 1.692	7.63 1227.8 1.698	7.73 1232.8 1.704	7.93 1242.8 1.715	8.13 1252.7 1.726	8.32 1262.6 1.737	8.52 1272.4 1.747	8.71 1282.3 1.758	9.18 1307.6 1.783	9.66 1331.4 1.806
55	69.7 (302.7)	6.24 1181.0 1.633	6.31 1185.8 1.638	6.50 1196.4 1.652	6.60 1201.5 1.658	6.69 1206.7 1.665	6.79 1211.8 1.671	6.88 1216.9 1.677	6.98 1222.0 1.683	7.07 1227.0 1.689	7.16 1232.0 1.695	7.35 1242.1 1.707	7.53 1252.0 1.718	7.71 1261.9 1.729	7.89 1271.9 1.739	8.07 1281.8 1.749	8.52 1306.2 1.775	8.95 1331.1 1.799
60	74.7 (307.4)	5.84 1182.4 1.627	5.84 1187.7 1.630	6.05 1195.3 1.643	6.15 1200.5 1.650	6.24 1205.8 1.656	6.32 1210.9 1.663	6.41 1216.1 1.669	6.50 1221.2 1.675	6.59 1226.2 1.681	6.67 1231.3 1.687	6.84 1241.4 1.699	7.01 1251.4 1.710	7.18 1261.5 1.721	7.36 1271.4 1.731	7.52 1281.4 1.741	7.94 1305.9 1.767	8.35 1330.7 1.791
65	79.7 (311.8)	5.50 1183.7 1.622	5.57 1189.0 1.628	5.66 1194.2 1.635	5.74 1199.5 1.642	5.82 1204.8 1.649	5.91 1209.9 1.655	5.99 1215.2 1.661	6.08 1220.4 1.667	6.16 1225.4 1.673	6.24 1230.5 1.679	6.40 1240.5 1.691	6.56 1250.8 1.702	6.72 1260.9 1.714	6.88 1270.8 1.724	7.04 1280.9 1.734	7.43 1305.5 1.760	7.82 1330.4 1.783
70	84.7 (316.0)	5.19 1185.0 1.617	5.23 1187.9 1.620	5.31 1193.1 1.627	5.39 1198.5 1.634	5.47 1203.8 1.641	5.55 1209.0 1.647	5.63 1214.3 1.654	5.71 1219.5 1.660	5.79 1224.6 1.666	5.87 1229.8 1.672	6.02 1240.0 1.684	6.17 1250.1 1.695	6.32 1260.3 1.706	6.47 1270.3 1.717	6.62 1280.4 1.727	6.99 1305.1 1.753	7.36 1330.0 1.777

TABLE II. THE PROPERTIES OF SUPERHEATED STEAM—continued

PRESSURE: <i>lb./sq. in.</i>		VOLUME: <i>cu.ft./lb.</i> TOTAL HEAT: <i>B.t.u./lb.</i> ENTROPY: <i>B.t.u./deg.F./lb.</i> } <i>at temperatures shown:—</i>																	
<i>gauge</i>																			
	<i>Abs. (Sat. temp. °F.)</i>	Sat.	330°F.	340°F.	350°F.	360°F.	370°F.	380°F.	390°F.	400°F.	410°F.	420°F.	430°F.	440°F.	460°F.	480°F.	500°F.	550°F.	600°F.
75	89.7 (320.1)	4.92 1186.1 1.612	5.00 1192.0 1.620	5.08 1197.4 1.627	5.16 1202.8 1.634	5.23 1208.1 1.640	5.30 1213.4 1.647	5.38 1218.6 1.653	5.45 1223.8 1.659	5.53 1229.0 1.665	5.60 1234.1 1.671	5.67 1239.4 1.677	5.74 1244.4 1.683	5.81 1249.5 1.688	5.96 1259.8 1.700	6.10 1269.8 1.710	6.24 1279.9 1.720	6.59 1304.8 1.746	6.94 1329.7 1.770
80	94.7 (323.9)	4.67 1187.2 1.608	4.73 1190.8 1.612	4.80 1196.4 1.619	4.87 1201.8 1.626	4.94 1207.1 1.633	5.01 1212.4 1.640	5.08 1217.7 1.646	5.15 1223.0 1.652	5.22 1228.3 1.658	5.29 1233.6 1.664	5.36 1238.9 1.670	5.43 1244.2 1.676	5.50 1249.5 1.681	5.64 1259.8 1.693	5.77 1269.3 1.703	5.91 1279.4 1.714	6.24 1304.4 1.740	6.57 1329.4 1.764
85	99.7 (327.7)	4.45 1188.1 1.604	4.48 1189.6 1.605	4.54 1195.3 1.613	4.61 1200.7 1.620	4.68 1206.1 1.626	4.75 1211.5 1.633	4.82 1216.8 1.640	4.89 1222.2 1.645	4.95 1227.4 1.652	5.02 1232.6 1.658	5.08 1237.9 1.664	5.15 1243.1 1.670	5.22 1248.5 1.675	5.35 1258.6 1.687	5.48 1268.8 1.697	5.61 1279.0 1.708	5.92 1304.0 1.734	6.24 1329.0 1.758
90	104.7 (331.2)	4.25 1189.1 1.600	—	4.32 1194.2 1.606	4.38 1199.7 1.613	4.45 1205.2 1.620	4.51 1210.6 1.627	4.58 1216.0 1.633	4.64 1221.4 1.639	4.71 1226.6 1.646	4.77 1231.9 1.652	4.83 1237.2 1.658	4.90 1242.4 1.664	4.96 1247.6 1.669	5.08 1258.0 1.681	5.21 1268.3 1.692	5.33 1278.5 1.702	5.63 1303.7 1.728	5.93 1328.7 1.752
95	109.7 (334.6)	4.07 1189.8 1.596	—	4.11 1193.1 1.600	4.17 1198.6 1.607	4.24 1204.2 1.614	4.30 1209.7 1.620	4.36 1215.1 1.627	4.42 1220.5 1.633	4.48 1225.8 1.640	4.54 1231.2 1.646	4.61 1236.5 1.652	4.67 1241.7 1.658	4.73 1247.0 1.664	4.85 1257.4 1.675	4.96 1267.8 1.686	5.08 1278.0 1.697	5.37 1303.0 1.722	5.66 1328.3 1.747
100	114.7 (337.9)	3.90 1190.6 1.592	3.60 1203.2 1.608	3.70 1206.9 1.603	3.81 1212.4 1.610	3.87 1218.0 1.617	3.92 1223.5 1.624	3.98 1228.9 1.630	4.03 1234.3 1.636	4.08 1239.6 1.642	4.14 1245.0 1.648	4.19 1250.4 1.654	4.25 1255.6 1.660	4.30 1260.9 1.665	4.35 1266.1 1.670	4.45 1276.5 1.681	4.71 1302.0 1.707	4.97 1327.2 1.732	5.46 1377.2 1.778
120	134.7 (350.1)	3.34 1193.3 1.579	3.41 1205.0 1.587	3.46 1206.9 1.593	3.51 1210.6 1.600	3.57 1216.3 1.607	3.62 1221.8 1.614	3.67 1227.3 1.620	3.72 1232.8 1.626	3.77 1238.2 1.632	3.82 1243.6 1.638	3.87 1249.1 1.644	3.92 1254.5 1.650	3.97 1259.8 1.656	4.02 1265.0 1.661	4.11 1275.5 1.672	4.35 1301.1 1.698	4.59 1326.5 1.723	5.05 1376.7 1.769
130	144.7 (355.6)	3.12 1194.5 1.573	3.16 1208.0 1.577	3.21 1208.0 1.584	3.26 1214.5 1.590	3.30 1220.2 1.597	3.35 1225.8 1.604	3.40 1231.3 1.611	3.45 1236.8 1.617	3.50 1242.3 1.623	3.54 1247.8 1.629	3.59 1253.2 1.635	3.64 1258.6 1.641	3.68 1264.0 1.647	3.73 1269.4 1.653	3.82 1274.4 1.664	4.04 1300.3 1.690	4.27 1325.8 1.714	4.70 1376.2 1.760
140	154.7 (360.9)	2.93 1195.7 1.568	—	2.98 1201.0 1.574	3.03 1206.9 1.581	3.08 1212.7 1.588	3.12 1218.5 1.595	3.17 1224.2 1.602	3.21 1229.8 1.608	3.26 1235.4 1.615	3.30 1241.0 1.621	3.35 1246.5 1.627	3.39 1252.0 1.633	3.43 1257.4 1.639	3.48 1262.8 1.644	3.56 1273.4 1.656	3.78 1299.4 1.682	3.98 1325.1 1.706	4.39 1375.6 1.752

TABLE II. THE PROPERTIES OF SUPERHEATED STEAM—continued

PRESSURE: lb./sq. in.		VOLUME: cu. ft./lb. } TOTAL HEAT: B.t.u./lb. } ENTROPY: B.t.u./deg. F./lb. } at temperatures shown:—																	
gauge	Abs. (Sat. temp. ° F.)	Sat.	380° F.	390° F.	400° F.	410° F.	420° F.	430° F.	440° F.	450° F.	460° F.	470° F.	480° F.	490° F.	500° F.	550° F.	600° F.	650° F.	700° F.
160	174.7 (370.7)	2.61 1197.5 1.558	2.66 1203.3 1.564	2.70 1209.3 1.571	2.74 1215.1 1.578	2.78 1221.0 1.585	2.82 1226.8 1.592	2.86 1232.5 1.598	2.90 1238.1 1.604	2.94 1243.7 1.611	2.98 1249.3 1.616	3.02 1254.9 1.622	3.06 1260.3 1.628	3.10 1265.8 1.634	3.14 1271.2 1.640	3.14 1271.2 1.640	3.33 1287.6 1.666	3.52 1323.5 1.692	3.70 1349.1 1.715
180	194.7 (379.6)	2.35 1199.1 1.549	— 1205.7 1.556	2.40 1211.9 1.562	2.44 1217.8 1.569	2.48 1223.6 1.576	2.51 1229.4 1.582	2.55 1235.2 1.588	2.59 1240.9 1.593	2.62 1246.7 1.598	2.66 1252.4 1.601	2.69 1258.1 1.607	2.73 1263.8 1.613	2.77 1269.5 1.620	2.80 1275.2 1.625	2.80 1275.2 1.625	2.97 1291.6 1.652	3.14 1327.0 1.678	3.31 1352.7 1.702
200	214.7 (387.7)	2.14 1200.4 1.541	— 1202.1 1.541	2.15 1208.4 1.549	2.19 1214.5 1.556	2.22 1220.4 1.563	2.26 1226.6 1.569	2.29 1232.4 1.575	2.32 1238.4 1.581	2.36 1244.4 1.587	2.39 1250.4 1.592	2.42 1256.4 1.598	2.46 1262.4 1.601	2.49 1268.4 1.607	2.52 1274.4 1.613	2.52 1274.4 1.613	2.68 1290.8 1.640	2.84 1326.6 1.666	2.99 1352.6 1.690
220	234.7 (395.5)	1.96 1201.5 1.533	— 1202.1 1.533	1.99 1207.7 1.541	2.02 1213.4 1.548	2.06 1219.4 1.554	2.09 1225.4 1.560	2.12 1231.4 1.566	2.15 1237.4 1.571	2.18 1243.4 1.577	2.21 1249.4 1.582	2.24 1255.4 1.588	2.28 1261.4 1.593	2.30 1267.4 1.598	2.30 1267.4 1.598	2.30 1267.4 1.598	2.45 1283.8 1.629	2.59 1319.0 1.656	2.73 1344.5 1.680
240	254.7 (402.7)	1.81 1202.5 1.526	— 1202.5 1.526	— 1207.5 1.532	1.85 1213.0 1.538	1.88 1219.0 1.545	1.91 1225.0 1.551	1.94 1231.0 1.557	1.97 1237.0 1.562	2.00 1243.0 1.568	2.03 1249.0 1.574	2.06 1255.0 1.580	2.09 1261.0 1.585	2.11 1267.0 1.591	2.11 1267.0 1.591	2.11 1267.0 1.591	2.25 1283.4 1.620	2.38 1318.0 1.646	2.51 1343.5 1.670
260	274.7 (409.3)	1.68 1203.2 1.519	1.73 1210.3 1.527	1.76 1216.7 1.534	1.78 1223.1 1.541	1.81 1229.5 1.548	1.84 1235.8 1.555	1.87 1242.0 1.562	1.89 1248.3 1.569	1.92 1254.6 1.575	1.94 1260.9 1.581	1.97 1267.2 1.588	2.00 1273.5 1.593	2.03 1279.8 1.600	2.03 1279.8 1.600	2.03 1279.8 1.600	2.20 1305.1 1.637	2.32 1340.0 1.662	2.44 1365.6 1.685
280	294.7 (415.8)	1.57 1203.9 1.513	1.59 1210.5 1.516	1.62 1216.9 1.523	1.65 1223.3 1.531	1.67 1229.7 1.538	1.70 1236.1 1.545	1.73 1242.5 1.552	1.75 1248.9 1.559	1.78 1255.3 1.566	1.80 1261.7 1.572	1.83 1268.1 1.579	1.85 1274.5 1.586	1.88 1280.9 1.593	1.88 1280.9 1.593	1.88 1280.9 1.593	2.04 1306.4 1.633	2.16 1341.7 1.658	2.27 1368.3 1.677
300	314.7 (421.7)	1.47 1204.4 1.507	— 1204.4 1.507	1.50 1210.5 1.513	1.53 1216.9 1.521	1.56 1223.3 1.528	1.58 1229.7 1.536	1.61 1236.1 1.543	1.63 1242.5 1.550	1.66 1248.9 1.557	1.68 1255.3 1.563	1.71 1261.7 1.570	1.73 1268.1 1.577	1.76 1274.5 1.584	1.76 1274.5 1.584	1.76 1274.5 1.584	1.90 1301.8 1.620	2.00 1337.7 1.645	2.09 1363.7 1.669
320	334.7 (427.5)	1.39 1204.9 1.502	— 1204.9 1.502	1.40 1210.5 1.508	1.43 1216.9 1.515	1.45 1223.3 1.522	1.48 1229.7 1.529	1.50 1236.1 1.536	1.53 1242.5 1.543	1.55 1248.9 1.550	1.57 1255.3 1.557	1.60 1261.7 1.564	1.62 1268.1 1.571	1.64 1274.5 1.578	1.64 1274.5 1.578	1.64 1274.5 1.578	1.79 1307.1 1.612	1.89 1343.0 1.638	1.99 1369.0 1.661
340	354.7 (433.0)	1.31 1205.1 1.497	— 1205.1 1.497	— 1205.1 1.497	1.34 1210.3 1.502	1.36 1216.7 1.509	1.38 1223.1 1.516	1.41 1229.5 1.523	1.43 1235.9 1.530	1.45 1242.3 1.537	1.47 1248.7 1.544	1.50 1255.1 1.551	1.52 1261.5 1.558	1.54 1267.9 1.565	1.54 1267.9 1.565	1.54 1267.9 1.565	1.68 1304.0 1.604	1.78 1340.0 1.630	1.87 1365.9 1.654

TABLE II. THE PROPERTIES OF SUPERHEATED STEAM—continued

PRESSURE: lb./sq. in.		VOLUME: cu. ft./lb. { at temperatures shown: — TOTAL HEAT: B.t.u./lb. { ENTROPY: B.t.u./deg. F./lb. }																			
		Abs. (Sat. temp. ° F.)		Sat.	450° F.	460° F.	470° F.	480° F.	490° F.	500° F.	520° F.	540° F.	560° F.	580° F.	600° F.	620° F.	640° F.	660° F.	680° F.	700° F.	750° F.
gauge	360	374.7 (438.3)	1.24 1205.4 1.492	1.28 1213.1 1.501	1.30 1220.2 1.508	1.32 1227.3 1.515	1.34 1234.2 1.523	1.37 1241.1 1.530	1.39 1247.8 1.537	1.43 1254.9 1.544	1.47 1262.0 1.551	1.51 1269.1 1.558	1.55 1276.2 1.565	1.59 1283.3 1.572	1.63 1290.4 1.579	1.67 1297.5 1.586	1.71 1304.6 1.593	1.75 1311.7 1.600	1.79 1318.8 1.607	1.83 1325.9 1.614	1.87 1333.0 1.621
	380	394.7 (443.3)	1.18 1205.5 1.487	1.20 1213.2 1.492	1.22 1220.3 1.500	1.25 1227.4 1.507	1.27 1234.5 1.515	1.29 1241.6 1.522	1.31 1248.7 1.529	1.35 1255.8 1.536	1.39 1262.9 1.543	1.43 1270.0 1.550	1.47 1277.1 1.557	1.51 1284.2 1.564	1.55 1291.3 1.571	1.59 1298.4 1.578	1.63 1305.5 1.585	1.67 1312.6 1.592	1.71 1319.7 1.599	1.75 1326.8 1.606	1.79 1333.9 1.613
400	414.7 (448.1)	1.12 1205.6 1.482	1.13 1213.3 1.484	1.16 1220.4 1.491	1.18 1227.5 1.499	1.20 1234.6 1.507	1.22 1241.7 1.514	1.24 1248.8 1.522	1.28 1255.9 1.529	1.32 1263.0 1.536	1.36 1270.1 1.543	1.40 1277.2 1.550	1.44 1284.3 1.557	1.48 1291.4 1.564	1.52 1298.5 1.571	1.56 1305.6 1.578	1.60 1312.7 1.585	1.64 1319.8 1.592	1.68 1326.9 1.599	1.72 1334.0 1.606	
	420	434.7 (452.8)	1.07 1205.6 1.478	— — —	1.09 1213.4 1.483	1.11 1220.5 1.491	1.13 1227.6 1.499	1.15 1234.7 1.507	1.17 1241.8 1.514	1.21 1248.9 1.522	1.25 1256.0 1.529	1.29 1263.1 1.536	1.33 1270.2 1.543	1.37 1277.3 1.550	1.41 1284.4 1.557	1.45 1291.5 1.564	1.49 1298.6 1.571	1.53 1305.7 1.578	1.57 1312.8 1.585	1.61 1319.9 1.592	1.65 1327.0 1.599
450	464.7 (459.5)	1.00 1205.5 1.472	— — —	— — —	1.03 1213.3 1.479	1.05 1220.4 1.488	1.07 1227.5 1.495	1.09 1234.6 1.503	1.12 1241.7 1.510	1.16 1248.8 1.517	1.20 1255.9 1.524	1.24 1263.0 1.531	1.28 1270.1 1.538	1.32 1277.2 1.545	1.36 1284.3 1.552	1.40 1291.4 1.559	1.44 1298.5 1.566	1.48 1305.6 1.573	1.52 1312.7 1.580	1.56 1319.8 1.587	
	500	514.7 (470.0)	.902 1205.3 1.462	.930 1213.0 1.469	.949 1220.7 1.478	.966 1228.5 1.485	.983 1235.4 1.492	1.00 1242.3 1.500	1.03 1249.2 1.507	1.06 1256.1 1.514	1.09 1263.0 1.521	1.12 1269.9 1.528	1.15 1276.8 1.535	1.18 1283.7 1.542	1.21 1290.6 1.549	1.24 1297.5 1.556	1.27 1304.4 1.563	1.30 1311.3 1.570	1.33 1318.2 1.577	1.36 1325.1 1.584	1.39 1332.0 1.591
550	564.7 (479.7)	.820 1204.7 1.453	— — —	.845 1212.8 1.461	.862 1220.4 1.469	.879 1228.2 1.476	.896 1235.1 1.483	.913 1242.0 1.490	.930 1248.9 1.497	.947 1255.8 1.504	.964 1262.7 1.511	.981 1269.6 1.518	1.00 1276.5 1.525	1.01 1283.4 1.532	1.03 1290.3 1.539	1.04 1297.2 1.546	1.06 1304.1 1.553	1.08 1311.0 1.560	1.10 1317.9 1.567	1.13 1324.8 1.574	
	600	614.7 (488.8)	.750 1203.9 1.444	.763 1210.8 1.445	.776 1217.8 1.446	.789 1224.8 1.447	.802 1231.8 1.448	.815 1238.8 1.449	.828 1245.8 1.450	.841 1252.8 1.451	.854 1259.8 1.452	.867 1266.8 1.453	.880 1273.8 1.454	.893 1280.8 1.455	.906 1287.8 1.456	.919 1294.8 1.457	.932 1301.8 1.458	.945 1308.8 1.459	.958 1315.8 1.460	.971 1322.8 1.461	.984 1329.8 1.462
650	664.7 (497.3)	.692 1202.9 1.436	— — —	.705 1209.8 1.437	.718 1216.8 1.438	.731 1223.8 1.439	.744 1230.8 1.440	.757 1237.8 1.441	.770 1244.8 1.442	.783 1251.8 1.443	.796 1258.8 1.444	.809 1265.8 1.445	.822 1272.8 1.446	.835 1279.8 1.447	.848 1286.8 1.448	.861 1293.8 1.449	.874 1300.8 1.450	.887 1307.8 1.451	.900 1314.8 1.452	.913 1321.8 1.453	.926 1328.8 1.454
	700	714.7 (505.4)	.641 1201.8 1.429	— — —	.654 1208.8 1.430	.667 1215.8 1.431	.680 1222.8 1.432	.693 1229.8 1.433	.706 1236.8 1.434	.719 1243.8 1.435	.732 1250.8 1.436	.745 1257.8 1.437	.758 1264.8 1.438	.771 1271.8 1.439	.784 1278.8 1.440	.797 1285.8 1.441	.810 1292.8 1.442	.823 1299.8 1.443	.836 1306.8 1.444	.849 1313.8 1.445	.862 1320.8 1.446

TABLE II. THE PROPERTIES OF SUPERHEATED STEAM—continued

Pressure: <i>lb./sq. in.</i>		VOLUME: <i>cu. ft. lb.</i> TOTAL HEAT: <i>B.t.u. lb.</i> ENTHALPY: <i>B.t.u./deg. F. lb.</i> } at temperatures shown: —																	
<i>gauge</i>	<i>Abs. (Sat. temp. ° F.)</i>	Sat.	530°F.	540°F.	550°F.	560°F.	570°F.	580°F.	590°F.	600°F.	620°F.	640°F.	660°F.	680°F.	700°F.	750°F.	800°F.	850°F.	900°F.
800	814.7 (520.3)	557 1199.1 1.414	577 1208.8 1.423	591 1218.1 1.433	604 1227.0 1.442	617 1235.7 1.451	628 1243.9 1.459	640 1251.9 1.467	652 1259.6 1.474	663 1267.3 1.481	684 1282.0 1.495	706 1296.2 1.508	726 1310.1 1.520	745 1323.4 1.532	766 1336.3 1.544	786 1349.6 1.554	813 1367.8 1.570	857 1397.8 1.594	900 1426.0 1.616
900	914.7 (533.9)	— 1195.9 1.401	— 1202.4 1.407	504 1202.4 1.407	517 1212.6 1.417	529 1222.1 1.427	541 1231.4 1.437	554 1240.2 1.445	565 1248.8 1.453	576 1257.1 1.461	596 1273.0 1.476	617 1287.9 1.490	636 1302.4 1.502	655 1316.1 1.515	673 1329.6 1.526	688 1341.8 1.534	716 1361.8 1.554	758 1392.2 1.578	800 1422.2 1.601
1000	1014.7 (546.4)	— 1192.0 1.389	— 1207.1 1.403	— 1217.7 1.414	446 1196.4 1.393	459 1207.1 1.403	473 1217.7 1.414	485 1227.5 1.423	496 1236.8 1.432	508 1245.8 1.441	527 1263.0 1.457	547 1278.9 1.471	565 1294.2 1.485	582 1308.6 1.498	600 1322.6 1.510	640 1358.9 1.538	688 1386.9 1.564	749 1417.6 1.594	800 1447.2 1.623
1100	1114.7 (557.9)	— 1187.9 1.377	— 1190.7 1.380	— 1202.3 1.391	— 1213.3 1.402	401 1190.7 1.380	413 1202.3 1.391	424 1213.3 1.402	435 1223.6 1.412	447 1234.0 1.421	467 1252.0 1.439	486 1269.1 1.454	503 1285.3 1.469	521 1300.6 1.482	537 1315.3 1.494	575 1349.9 1.524	610 1413.2 1.550	646 1443.3 1.574	677 1463.3 1.596
1200	1214.7 (568.8)	— 1183.4 1.366	— 1185.1 1.368	— 1197.3 1.380	— 1208.3 1.390	— 1219.3 1.401	362 1185.1 1.368	373 1197.3 1.380	385 1209.3 1.390	396 1220.3 1.401	416 1240.2 1.420	435 1258.6 1.437	452 1275.9 1.453	468 1292.2 1.467	485 1307.6 1.480	522 1343.9 1.511	555 1377.4 1.538	588 1409.0 1.562	618 1439.5 1.585
1400	1414.7 (588.4)	— 1173.3 1.345	— 1188.7 1.359	— 1214.1 1.383	— 1236.4 1.404	— 1256.6 1.422	387 1274.9 1.438	402 1292.0 1.453	417 1308.6 1.466	430 1323.8 1.480	442 1338.7 1.491	455 1353.0 1.503	467 1367.0 1.514	478 1380.4 1.524	490 1393.6 1.535	501 1406.6 1.545	511 1419.2 1.555	522 1431.7 1.564	541 1451.7 1.584
1600	1614.7 (606.1)	— 1162.0 1.324	— 1183.6 1.344	— 1211.2 1.370	— 1239.0 1.390	— 1259.1 1.409	324 1256.1 1.409	340 1275.3 1.426	353 1293.3 1.441	366 1310.1 1.455	378 1326.2 1.469	389 1341.5 1.482	400 1356.1 1.494	410 1370.4 1.504	421 1384.2 1.515	431 1397.6 1.526	441 1410.7 1.535	451 1423.6 1.544	461 1436.0 1.553
1800	1814.7 (622.1)	— 1149.1 1.304	— 1181.4 1.324	— 1211.2 1.352	— 1239.0 1.380	— 1259.1 1.399	274 1234.8 1.380	289 1256.9 1.399	303 1276.9 1.417	314 1295.3 1.432	326 1312.7 1.447	337 1329.2 1.460	348 1344.7 1.473	358 1359.7 1.484	368 1374.2 1.496	377 1388.1 1.507	386 1401.8 1.516	395 1415.3 1.526	395 1428.6 1.536
2000	2014.7 (636.8)	— 1135.0 1.284	— 1141.4 1.291	— 1193 1.291	— 1239.0 1.324	— 1259.1 1.358	232 1209.8 1.351	246 1236.1 1.373	260 1259.0 1.393	273 1279.5 1.410	284 1298.3 1.426	295 1316.0 1.440	306 1332.7 1.454	316 1348.5 1.466	325 1363.8 1.478	333 1378.4 1.489	342 1392.6 1.500	350 1406.6 1.510	350 1417.0 1.516
3000	3014.7 (696.1)	— 1012.7 1.155	— 1107.4 1.155	— 1174.4 1.155	— 1208.7 1.155	— 1237.3 1.155	— 1255.5 1.155	— 1273.5 1.155	— 1291.5 1.155	— 1309.5 1.155	— 1327.5 1.155	— 1345.5 1.155	— 1363.5 1.155	— 1381.5 1.155	— 1399.5 1.155	— 1417.5 1.155	— 1435.5 1.155	— 1453.5 1.155	— 1471.5 1.155

INDEX

Abbreviations

App.	=	Appendix
C.T.F.	=	Coal Tar Fuel(s)
D. & C.	=	Drying and Conditioning
H. & V.	=	Heating and Ventilating
P.F.	=	Pulverized Fuel
S.H.	=	Space Heating

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